# Study on feasibility of SATCOM for railway communication

## Final Report

**ERA 2016 01 SC** **VERSION 1/1**

EUROPEAN UNION AGENCY FOR RAILWAYS

*The opinions expressed in this study are those of the authors and do not necessarily reflect the views of the European Union Agency for Railways*

indra

ALG TRANSPORTATION INFRASTRUCTURE & LOGISTICS

# Final Report

**Project : Study on feasibility of SATCOM for railway communication**

**Programme : -**

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# ACRONYMS

| | |
|---|---|
| ACM | Adaptive Coding Modulation |
| ATM | Air Traffic Management |
| BGAN | Broadband Global Area Network |
| CAPEX | Capital Expenditure |
| CBA | Cost Benefit Analysis |
| CCS | Control Command and Signalling |
| CDM | Code Division Multiplexing |
| CDMA | Code Division Multiple Access |
| CRC | Cyclic Redundancy Check |
| CRDSA | Contention Resolution Diversity Slotted ALOHA |
| CS | Communications Standard |
| DAMA | Demand Assigned Multiple Access |
| DVB-RCS | Digital Video Broadcasting – Return Channel Satellite |
| DVB-S2 | Digital Video Broadcasting – Satellite – Second Generation |
| DVB-S2X | DVB-S2 eXtension |
| EIRENE | European Integrated Railway Radio Enhanced Network |
| ERA | European Union Agency for Railways |
| ERTMS | European Rail Traffic Management System |
| E-SSA | Enhanced-Spread Spectrum ALOHA |
| ESA | European Space Agency |
| ETCS | European Train Control System |
| FDM | Frequency Division Multiplexing |
| FDMA | Frequency Division Multiple Access |
| FEC | Forward Error Correction |
| FRMCS | Future Railway Mobile Communication System |
| F-SIM | Fixed Satellite Interactive Multimedia |
| FSS | Fixed Satellite Services |
| GEO | Geostationary Earth Orbit |
| GES | Gateway Earth Station |
| GPRS | General Packet Radio System |
| GSM-R | Global System for Mobile Communications – Railway |
| GX | Global Xpress |
| HEO | Highly Elliptical Orbit |
| HLR | Home Location Register |
| HSL | High Speed Line |
| HTS | High Throughput Satellites |
| IM | Infrastructure Manager |
| IMS | IP Multimedia Subsystem |

| | |
|---|---|
| IP | Internet Protocol |
| IRR | Internal Rate of Return |
| ISL | Inter-Satellite Links |
| ITU | International Telecommunication Union |
| LEO | Low Earth Orbit |
| LNB | Low Noise Block |
| LTE | Long Term Evolution |
| M2M | Machine to Machine |
| MARR | Minimum Acceptable Rate of Return |
| MEO | Medium Earth Orbit |
| MF | Multi-Frequency |
| MODCOD | MODulation and CODing |
| MSS | Mobile Satellite Services |
| MTBF | Mean Time Between Failures |
| MTTR | Mean Time To Repair |
| MTTRS | Mean Time To ReStore |
| NGN | Next Generation Network |
| NPV | Net Present Value |
| OBP | On-Board Processing |
| OFDMA | Orthogonal Frequency Division Multiple Access |
| OPEX | Operational Expenditure |
| PAMA | Permanently Assigned Multiple Access |
| QoE | Quality of Experience |
| QoS | Quality of Service |
| RA | Random Access |
| RBC | Radio Block Centre |
| RPAS | Remotely Piloted Aircraft System |
| RT | Remote Terminal |
| RU | Railway Undertaking |
| SATCOM | SATellite COMmunications |
| SCADA | Supervisory Control And Data Acquisition |
| SLA | Service Level Agreement |
| S-MIM | S-band Mobile Interactive Multimedia |
| SOTM | SATCOM On The Move |
| TDM | Time Division Multiplexing |
| TDMA | Time Division Multiple Access |
| TOR | Terms Of Reference |
| TRL | Technology Readiness Level |
| TSI | Technical Specification for Interoperability |
| UIC | International Union of Railways |
| URS | User Requirements Specification |

| | |
|---|---|
| VLR | Visitor Location Register |

## ABSTRACT

With the aim of **assessing** the feasibility of the satellite communications (SATCOM) in the Future Railway Mobile Communication System (FRMCS), this study has analysed different SATCOM solutions comprising all the range of frequencies, orbits and waveforms most typically used for the SATCOM market, in order to provide a broad vision of the SATCOM capabilities.

Taking into account the timeframe for replacing the current GSM-R, the main conclusion of the study is that **none of the SATCOM solutions available analysed is fully compliant with the whole set of criteria identified**. It means that, from the technical point of view, **voice and data railway applications are not supported simultaneously** by any SATCOM solution according to railway safety critical applications requirements. This is mainly because GSM-R voice requirements become the main barrier for SATCOM, due principally to the fact that their values are out of the scope of any current SATCOM solution (in terms of availability, latency and even capacity for the whole European demand). Therefore, it is strongly recommended to reconsider such requirement's values (*i.e.* latency and availability) taking into account the **safety cases** for these scenarios where SATCOM could be working standalone (*e.g.* remote/rural areas).

However, and taking into account that railway voice applications are much more demanding and the main reason for the not compliance of several criteria, when only safety data applications (*i.e.* ETCS) are considered, most of the SATCOM solutions become technically feasible. This is because of more challenging criteria for SATCOM are easier to reach when applications data rates are lower, and when the most demanding type of terminal (*i.e.* the handheld) is not required anymore (since pedestrian users do not use ETCS data applications).

On the other hand, the study identifies long-term potential solutions (such as MEO C-band and IRIS FOC) that can fulfil the full set of criteria provided that they were also supported by terrestrial solutions/technology in the areas where there is a lack of satellite coverage (*e.g.* train stations, urban areas, tunnels, etc).

It is very important to remark that nowadays it does not exist a **regulatory framework** supporting the certification and homologation of the SATCOM solutions for the railway domain. Therefore, solutions technically compliant with railway criteria shall be upgraded in order to comply with these future established regulations.

Due to the stringent requirements from safety railway applications, it is well understood that the future railway communication architecture will be composed of several communications systems, *i.e. multi-link system*, as the *Next Generation Networks* tend. All these systems (terrestrial and satellite) will have to be integrated in order to jointly provide the expected service to the railway community. This integration implies, for example, the use of new elements capable to monitor all the systems involved and to take decisions about what communication system use at each time and how to execute smooth transitions among them (*i.e.* seamless vertical handovers), such as the *smart router*. It also includes the use of possible *gap fillers* (*i.e.* gateways capable to transform satellite signal to terrestrial and vice-versa), which will be used mainly to counteract geographical constraints (*e.g.* tunnels, mountains...) principally on route, *i.e.* in rural areas with a small number of users, since urban areas with lots users will be mainly covered by terrestrial systems.

In order to successfully deploy a SATCOM solution as part of the multi-technology railway architecture, several aspects have to be considered, such as the *regulatory framework*, *railway certifications*, the use of *communication standards*, *geographical constraints* and some other *technical implications* because of introducing SATCOM technologies into the railway field and in a multi-technology architecture. It is even of relevance to consider the SATCOM *market interest* to offer products and services for the railway domain, since without this interest the previous aspects can hardly be achieved.

Finally, and from the economic point of view of satellite solutions compared with terrestrial ones, it is worth mentioning that two main scenarios can be analysed: *Brownfield* (when considering terrestrial solutions deployed re-using current GSM-R infrastructure) and *Greenfield* (when deploying future terrestrial solutions from scratch). In this sense, SATCOM economic feasibility raises when deploying a railway communication system in a new line (*Greenfield*), since it is much cheaper (in terms of CAPEX) and faster to deploy than terrestrial solutions. This is because of ground infrastructure is not required in SATCOM solutions (except for those areas to be covered by alternatives terrestrial solutions due to the lack of satellite coverage).

# 1. EXECUTIVE SUMMARY

This is the executive summary of the Final Report for the “Study on feasibility of SATCOM for railway communication”, which has been conducted by Indra and ALG for the European Union Agency for Railways over the period June 2016 – February 2017.

This study is part of the activities carried out by the European Union Agency for Railways to explore the options and opportunities for the future communication systems for railways, taking into account the near-future GSM-R obsolescence (expected by 2030).

With this purpose, Indra and ALG have studied the feasibility of SATCOM solutions for railway communications, considering the requirements of railway applications and the key parameters and criteria of satellite communications. A broad market overview has been performed, taking into consideration different solutions with different key SATCOM parameters, in order to have the best possible view regarding SATCOM feasibility. These SATCOM solutions have been evaluated against the criteria previously identified in order to find the best SATCOM solutions for railways.

Cost-Benefit Analysis (CBA) are also included within this study in order to check the feasibility of SATCOM solutions from a non-technical point of view.

## 1.1 RAILWAY APPLICATIONS

User Requirement Specification (URS) document [AD-01] summarises a set of user requirements for the FRMCS, regardless of the communication technology (*i.e.* bearer) used. These requirements are based on the applications foreseen for the FRMCS. The URS describes relevant railway applications for the future railway mobile communication system(s), their classification and key parameters from a communications point of view.

Therefore, future railway communication applications have been classified into *Critical Communication Applications* (CA), *Performance Communication Applications* (PA) and *Business Communication Applications* (BA). In addition, for each one of these categories, additional *support* applications have also been defined, which provides cross services for the communication applications. Examples of applications in each category are summarised in Table 1.

| *Critical Communication Applications (CA)* | *Performance Communication Applications (PA)* |
|---|---|
| ▪ On-train voice communication from driver to controller(s) and vice-versa<br>▪ Multi-train voice communication for drivers including ground users<br>▪ Trackside maintenance voice communication<br>▪ Shunting voice/data communication<br>▪ Public emergency call<br>▪ Railway emergency communication<br>▪ Automatic train control/operations communication | ▪ On-train voice communication from train staff towards ground user(s) and vice-versa<br>▪ Multi-train voice communication for drivers excluding ground users<br>▪ On-train voice communication<br>▪ Communication at stations and depots<br>▪ Wireless on-train data communication for train staff<br>▪ M&C of non-critical infrastructure<br>▪ Real time video |

| *Business Communication Applications (BA)* | *Critical Support Applications (CSA)* |
|---|---|
| ▪ Inviting-a-user messaging<br>▪ Emergency help point for public<br>▪ Wireless internet on-train for passengers<br>▪ Wireless internet for passengers on platforms | ▪ Secured voice/data communication<br>▪ Location services<br>▪ Authorisation of voice/data communication<br>▪ Authorisation of applications<br>▪ Prioritisation<br>▪ Multi-user talker control |
| *Performance Support Applications (PSA)* | *Business Support Applications (BSA)* |
| ▪ Information help point for public | ▪ *(No BSA defined at URS v2.0)* |

Table 1: Examples of applications defined and categorised in the URS document

The main conclusions obtained from the data compiled for the critical application mentioned in the URS document are that:

- **High reliability** is required for these critical applications (in comparison to the performance and business ones).
- **Low latency** and **immediate setup** are highly demanded in most of the critical applications.
- **Voice calls shall be supported**, including user-to-user and multi-user.
- **Narrow**[1] **band systems** seem to be sufficient to support voice and data in critical applications.
- **Two-way communications** (*i.e.* 50/50 symmetry) are required for most of the critical applications.

These conclusions are taken into account in the parameters and criteria identification process (detailed in section §1.3), since they represent a key input for this process.

## 1.2 SATELLITE COMMUNICATION SYSTEM DESCRIPTION

### 1.2.1 Baseline Satcom system description

A satellite communications system (commonly referred to as SATCOM system) is a communication system that makes use of an artificial satellite launched into space to provide global telecommunications. A SATCOM system is mainly composed of three segments: *space segment*, *ground (or control) segment* and *user (or terminal) segment*, as can be seen in Figure 1.

[1] New future railway critical applications are being considered nowadays and could change this conclusion about narrow band systems and their ability to support the complete set of voice/data critical apps. For example, the transmission of a real-time video for ATO purposes is being discussed at present. If this application (or a similar one) is finally confirmed, this assumption will not be true.

However, it is interesting to point out that in other fields (such as the RPAS – *Remotely Piloted Aircraft System*) similar discussions have been addressed, and finally video applications have been discarded. In fact, video image processing is expected to be eventually performed on-board (thus avoiding the transmission of large amount of data through the return channel).

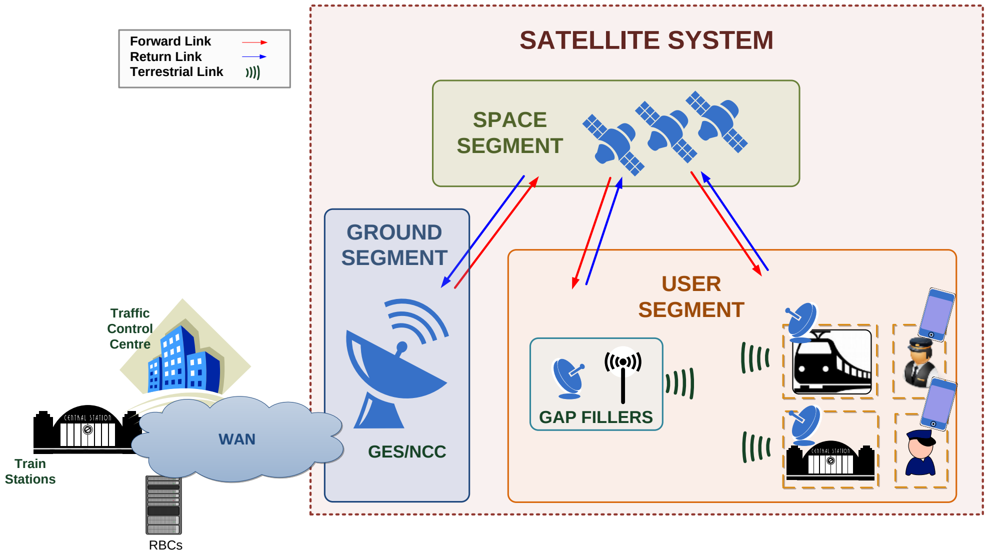


Figure 1: SATCOM system for the railway environment

SATCOM services can be further broken down into *fixed* versus *mobile* services. *Fixed* SATCOM services operate from a terminal on the ground at a fixed location, whereas *mobile* counterparts are transmitted from a terminal that can be in motion or temporarily stationary at the time of communication (such as a ship, aircraft or land vehicle). *Mobile* SATCOM services have traditionally provided voice and low data rate services up to about 0.5 Mb/s but, more recently, services derived from fixed satellite systems have become available offering more than 10 Mb/s.

### 1.2.2 Multi-technology communication architecture description

The coverage of mobile satellite communications (satellite visibility) cannot always be assured throughout the required area. In the railway domain (for example), tunnels and shadowing zones due to buildings, trees, etc. provide an obstacle to satellite coverage. To solve this issue, the use of *gap fillers* and/or additional (terrestrial) communications systems is required. Therefore, the introduction of SATCOM within the railway domain also requires the use of terrestrial solutions.

In parallel, the Next Generation Network (NGN) concept separates applications from transport networks (bearers), and allows the coexistence of different communications systems regardless of their applications, which will be used according to, for example, the type of terminal and/or availability.

Therefore, this network trend, where several systems of different natures can coexist to provide service to independent applications, facilitates the introduction of satellite communications within the railway domain. SATCOM can thus be used as a bearer (main or backup) to cover (for example) remote areas with small number of users where terrestrial communication system deployment could be complex and too much expensive.

Figure 2 shows a complete communication architecture combining both satellite and terrestrial systems in order to provide full coverage in the possible future railway scenarios.

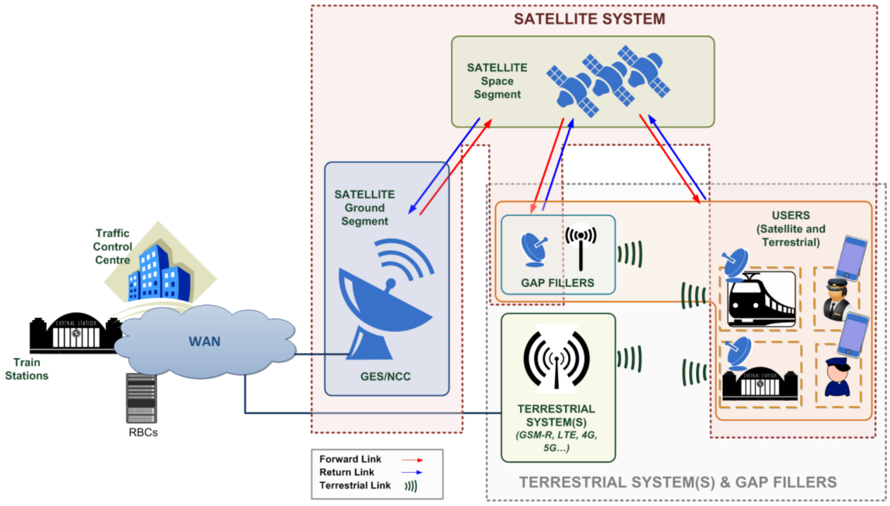


Figure 2: Railway communication architecture including SATCOM and terrestrial systems

## 1.3 IDENTIFICATION OF CRITERIA FOR THE ASSESSMENT OF SATCOM SOLUTIONS

Three types of criteria have been identified for the subsequent assessment of the SATCOM solutions proposed regarding their feasibility to support critical railway applications:

- Technical and functional criteria
- Multi-technology criteria
- Non-technical and non-functional criteria

A high-level definition similar to the one used within the URS document [AD-01] has been used in the description of the criteria identified.

The tables below summarise the criteria to be applied to the proposed SATCOM solutions.

| *Technical and functional criteria* | |
|---|---|
| ***Criterion ID*** | ***Criterion*** |
| **CRT-TECH-1** | The "**link availability**" of the proposed SATCOM system shall be **High**. |
| **CRT-TECH-2** | The "**reliability**" of the proposed SATCOM system shall be **High**. |
| **CRT-TECH-3** | The end-to-end **error ratio** of the proposed SATCOM system shall be **Low**. |
| **CRT-TECH-4** | **Transfer delay** for the proposed satellite system shall be **Low**. |
| **CRT-TECH-5** | **Delay jitter** of the proposed SATCOM system shall be **Low**. |
| **CRT-TECH-6** | Network **registration delay** shall be **Normal** (with similar values to GSM-R). |
| **CRT-TECH-7** | The **call establishment delay** for the proposed SATCOM system shall be **Low**. |

| | |
|---|---|
| **CRT-TECH-8** | The proposed SATCOM system shall allow (at least) the estimated number of European FRMCS **users** by 2030 registered simultaneously. |
| **CRT-TECH-9** | The proposed SATCOM system shall provide **priority** and **pre-emption** mechanisms. |
| **CRT-TECH-10** | The proposed SATCOM system shall support **Data** and **Voice** services. |
| **CRT-TECH-11** | The proposed SATCOM system shall support as minimum Low bandwidth applications |
| **CRT-TECH-12** | "*user-to-user*" -"*multi-user*" and "*uni-directional*" – "*bi-directional*" **types of communications** for both voice and data services shall be provided. |
| **CRT-TECH-13** | The minimum required **coverage** of the SATCOM system shall be **Europe**. |
| **CRT-TECH-14** | The SATCOM system shall provide communications for remote terminals when stationary and when travelling at speeds up to the maximum allowable line speed or **500 km/h**, whichever is the lower. |
| **CRT-TECH-15** | The proposed SATCOM system shall be **flexible** to support (at least) new created apps in the future. |
| **CRT-TECH-16** | The proposed SATCOM system shall be highly and easily **scalable**. |
| **CRT-TECH-17** | The following types of terminals shall be provided: "On-board (mobile)", "Handheld" and "Fixed". |
| **CRT-TECH-18** | The proposed SATCOM system shall provide **high level of safety** in the information exchanged. |
| **CRT-TECH-19** | The proposed SATCOM system shall provide **high level of security** in the information exchanged. |

Table 2: Summary of the technical and functional criteria identified

| ***Multi-technology criteria*** | |
|---|---|
| ***Criterion ID*** | ***Criterion*** |
| **CRT-MULT-1** | All communication networks (*e.g.* SATCOM and terrestrial) of the future railway communications architecture shall be **Packet-Switched** (PS), since all the applications supported shall be **IP based**. |
| **CRT-MULT-2** | The end-to-end **QoS** of a communication call/session shall be **guaranteed** according to user's SLA. |
| **CRT-MULT-3** | **Handovers** among systems (aka vertical handovers) shall be **transparent** to users (*i.e.* seamless). |
| **CRT-MULT-4** | **Terminals** shall support **multi-technology** in order to avoid having one different terminal per technology. |

Table 3: Summary of the multi-technology criteria identified

| ***Non-technical and non-functional criteria*** | |
|---|---|
| ***Criterion ID*** | ***Criterion*** |
| **CRT-NONT-1** | Sustained **lifecycle** covering the full FRMCS timespan without obsolescence |

| | |
|---|---|
| CRT-NONT-2 | Easy serviceability through an acceptable **dispatch rate**, including maintenance time |
| CRT-NONT-3 | At least an **acceptable cost efficiency**, COTS-based and deployable in under 10 years |
| CRT-NONT-4 | Full lifecycle cost, by all acceptable estimates, **lower than GSM-R**. |
| CRT-NONT-5 | Full lifecycle **Economic IRR** (*Internal Rate of Return*) above the average MARR (*Minimum Acceptable Rate of Return*) of the Member States. |
| CRT-NONT-6 | Mandatory certification and interoperability **standards** shall ensure integration. |
| CRT-NONT-7 | **TRL of 7 or above** shall ensure full-system prototype level operational success. |

Table 4: Summary of the non-technical and non-functional criteria identified

## 1.4 SATCOM MARKET SURVEY

With the aim of providing a broad view of the different SATCOM systems and their adaptability to the railway domain, the market survey takes into account several solutions with different values regarding key architectural aspects/parameters of satellite communications. These "key architectural aspects" that characterise the SATCOM solution are:

- **Satellite orbit**. This aspect determines, among other factors: the propagation delay, the use of some types of terminals (*e.g.* handheld) and has an impact on the complexity of solutions—not only for the space segment, but also ground and user segments, since the satellite orbit determines, for example, if certain types of antennas (directive, omnidirectional) can or cannot be enabled.
- **Frequency band**. This is an important system parameter, since final features of the solution, such as the bandwidth available or atmospheric signal degradation, depend directly on the frequency band selected. In this regard, for example, higher frequency bands give access to broader bandwidths. However, they are also more susceptible to signal degradation due to rain fade (the absorption of radio signals by atmospheric rain, snow or ice). Figure 3 summarises SATCOM frequency bands and their main capabilities.

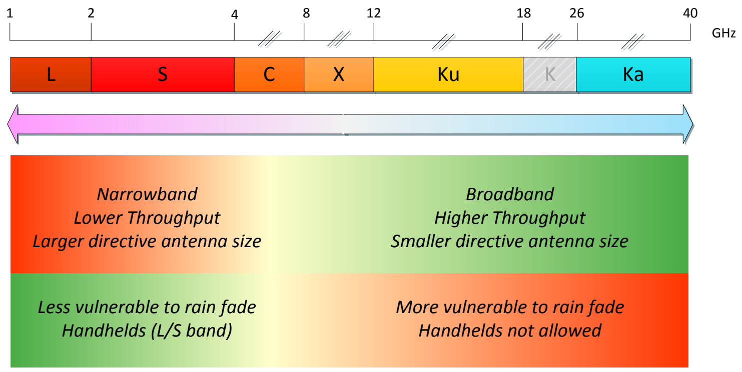


Figure 3: SATCOM frequency bands and main capabilities

- **Signal waveform / Air interface.** This is an essential aspect of the system's performance, since the modulation, codification and the different features implemented within the satellite signal are key parameters to counteract fast fading of the railway channel caused by the existence of catenaries, power arches, shadowing, etc.

Taking into consideration these 3 key elements of a SATCOM system, several current and future SATCOM solutions (either underway, planned or simply evolutions of current systems) have been identified and taken into account in the assessment. Table 5 below summarises the different solutions identified in the survey, which will be assessed subsequently. These solutions cover ranges of possible values of satellite orbit, frequency bands and air interface, providing a broad vision of the SATCOM possibilities within the railway domain.

| *Satcom solutions* | | | *Description* |
|---|---|---|---|
| *LEO* | 1 | Iridium NEXT | Iridium NEXT is a near-future LEO constellation (currently underway) that is going to replace the original Iridium constellation. With its 66 operational satellites, it provides full coverage to the Earth offering voice and data services.<br>Iridium NEXT operates the L-band (like the former Iridium) but also the Ka band to provide broadband services to fixed terminals. |
| *MEO* | 2 | MEO / C-band<br>(DVB-S2X – DVB-RCS2+M) | This solution is neither in development nor planning stage, but has been analysed since it was the most suitable candidate of the Satcom4Rail study [RD-02].<br>There exists a similar solution based on MEO/S-band (ICO), but it is reaching the end of its life cycle. |
| *GEO* | 3 | Inmarsat 4/6 (GEO / L-band) | Inmarsat 4 is a GEO / L-band solution that provides voice and data services worldwide with a current constellation of 3 GEO satellites[2].<br>Inmarsat 6 is set to become the evolution of current Inmarsat 4, including several improvements in performance and new services. |
| | 4 | GEO / L-band + ANTARES CS<br>(IRIS FOC) | It has been considered useful to analyse a GEO / L-band solution using a communication standard (CS) based on a pure random multiple access (just like the ANTARES CS, which was conceived to meet with Air Traffic Management requirements). It is assumed that the future IRIS FOC (developed under ESA program ARTES 10) is aiming to include similar features beyond 2025[3]. |
| | 5 | Thuraya (GEO / L-band) | This is an appealing solution since this system is able to provide coverage by means of a satellite system (GEO satellites operating at L-band) fully compatible with terrestrial GSM networks (increasing this way the availability required for critical applications). |
| | 6 | GEO / S-band<br>(S-MIM) | This solution is very similar to a GEO / L-band. Therefore, it will be analysed with regard to a different air interface than the previous GEO / L-band solutions. In this case, the S-MIM standard is taken into account. This standard was conceived for mobile applications supporting handhelds and enabling hybrid solutions combining satellite and terrestrial bearers. |

[2] It is taken into account the performances from SwiftBroadband (BGAN) service conceived for providing aeronautical services.

[3] According to SESAR Master Plan 2015

| | | | |
|---|---|---|---|
| | 7 | GEO / C-band (DVB-S2X – DVB-RCS2+M) | Again, this solution will be similar to previous GEO / L and GEO / S bands. C-band provides more bandwidth than L and S-bands, but it is a higher band and it is more affected by weather conditions. This solution will be analysed with CS DVB-S2X in the forward link and DVB-RCS2+M in the return link. |
| | 8 | GEO / X-band (DVB-S2X – DVB-RCS2+M) | This solution, despite its similarity to the previous GEO/C-band, holds interest for analysis as GovSatcom initiatives that are going to provide safety & security applications to the European members are going to take advantage of the military and governmental reserved bands (X-band and a portion of the Ka-band). |
| | 9 | SmartLNB (F-SIM) | Despite the fact that SmartLNB is based on GEO / Ku/Ka bands, it is very attractive for analysis since its return link is based on the S-MIM CS, which relies on a pure random multiple access offering very narrow band services. |
| | 10 | GEO / Ku-band (DVB-S2X – DVB-RCS2+M) | This solution is similar to the SmartLNB system regarding orbit and frequency band. But in this case it will be analysed with regard to more traditional air interfaces based on DVB standards, mainly for the return link. Therefore, a DVB-S2X is considered for the forward link, and a DVB-RCS2+M for the return link. |
| | 11 | Inmarsat 5 (GEO / Ka-band) | Inmarsat SATCOM system that provides broadband services by means of Ka-band high-throughput satellites (HTS). Currently there are 3 GEO satellites providing service worldwide, and another one is under development to increase capacity. Air interface will be based on DVB family, in particular on TDM/MF-TDMA for the forward and return link, respectively. |

Table 5: List of Satcom solutions to be analysed

## 1.5 SATCOM SOLUTIONS ASSESSMENT

The assessment of the SATCOM solutions proposed in Table 5 is mainly **qualitative**, although complementary quantitative analyses have also been performed for the justification of some criteria. It is worth mentioning that the criteria evaluation has been performed assuming that the SATCOM solution is working on its own (*i.e.* when any other terrestrial solution is available). The objective is to evaluate each criterion for each SATCOM solution and determine if they are Compliant (C), Partially Compliant (PC), Non-Compliant (NC) or Not Applicable (N/A). A justification or explanation is also provided in order to clarify and justify the assessment. Bearing in mind that the main part of the assessment is qualitative, it has been considered important to add **extra granularity** to the *compliance* evaluation of the technical and multi-technology criteria. In this way, it is easier to differentiate the systems that clearly comply with a particular criterion from other ones that could comply (and in fact are marked as compliant) but present more difficulties or are affected by other factors. Thus, the evaluation is more accurate and facilitates the process of drawing conclusions.

Therefore, Table 6 summarises possible evaluation results used in the assessment.

| *Value* | | *Meaning* |
|---|---|---|
| **C** | **C (High)** | Compliant (*High*) |
| | **C** | Compliant (*Normal*) |
| | **C (Low)** | Compliant (*Low*) |
| **PC** | | Partially Compliant |
| **NC** | | Non-Compliant |
| **N/A** | | Not Applicable |
| **Unk** | | Unknown |

Table 6: Values for the technical criteria evaluation

Figure 4 shows the evaluation result of the technical and functional criteria.

| Criterion ID | Satcom technology | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| | Iridium NEXT | MEO / C-band | Inmarsat 4 (BGAN) - Inmarsat 6 (ICE) | IRIS FOC | Thuraya | GEO / S-band | GEO / C-band | GEO / X-band | SmartLNB | GEO / Ku-band | Inmarsat 5 (Global Xpress) |
| CRT-TECH-1 | NC | C | NC | C (Low) | NC | C (Low) | C (Low) | NC | NC | NC | NC |
| CRT-TECH-2 | C (Low) | C (High) | C (Low) | C (High) | C (Low) | C (Low) | C (High) | C (High) | C (High) | C (High) | C (High) |
| CRT-TECH-3 | C | C | C | C | C | C | C | C | C | C | C |
| CRT-TECH-4a | C (High) | C (High) | NC | C (Low) | C (Low) | NC | C (Low) | C (Low) | NC | C (Low) | C (Low) |
| CRT-TECH-4b | C (High) | C (High) | NC | NC | NC | NC | NC | NC | NC | NC | NC |
| CRT-TECH-5 | C (High) | C (High) | C (Low) | C (Low) | C (Low) | C (Low) | C (Low) | C (Low) | C (Low) | C (Low) | C (Low) |
| CRT-TECH-6 | C | C | NC | C | C | C | C | C | C | C | NC |
| CRT-TECH-7 | NC | C | NC | C (High) | NC | C (High) | C | C | C (High) | C | C |
| CRT-TECH-8 | NC | C | PC | C | NC | C | C | C | C | C | C |
| CRT-TECH-9 | C | C | C | C | C | C | C | C | C | C | C |
| CRT-TECH-10 | C | C | C | C (Low) | C | PC | C | C | PC | C | C |
| CRT-TECH-11 | C | C | C | C (Low) | C (Low) | C (Low) | C | C | C | C (High) | C (High) |
| CRT-TECH-12 | NC | C | NC | C | NC | C | C | C | C | C | NC |
| CRT-TECH-13 | C | C | C | C | C | C | C | C | C | C | C |
| CRT-TECH-14 | C | C | C | C | NC | C | C | C | PC | C | C |
| CRT-TECH-15 | C (Low) | C (High) | C | C (Low) | C (Low) | C (Low) | C (High) | C (High) | C (Low) | C (High) | C (High) |
| CRT-TECH-16 | C (Low) | C (Low) | C (Low) | C (Low) | NC | C (Low) | C (High) | C | C (High) | C (High) | C (Low) |
| CRT-TECH-17 | C (Low) | C | C (Low) | PC | C (Low) | C | PC | PC | PC | PC | PC |
| CRT-TECH-18 | C (Low) | C (High) | C (High) | C (High) | C (Low) | C (High) | C (High) | C (High) | C (High) | C (High) | C (High) |
| CRT-TECH-19 | NC | NC | C | NC | NC | PC | NC | NC | PC | NC | NC |

Figure 4: Technical and functional criteria compliance matrix

Figure 5 shows the evaluation result of the multi-technology criteria.

| Criterion ID | Satcom technology | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| | Iridium NEXT | MEO / C-band | Inmarsat 4 (BGAN) - Inmarsat 6 (ICE) | IRIS FOC | Thuraya | GEO / S-band | GEO / C-band | GEO / X-band | SmartLNB | GEO / Ku-band | Inmarsat 5 (Global Xpress) |
| CRT-MULT-1 | C (Low) | C (High) | C (Low) | C | C (Low) | C | C (High) | C (High) | C | C (High) | C (High) |

Figure 5: Multi-technology criteria compliance matrix

Finally, Figure 6 shows the evaluation result of the non-technical and non-functional criteria.

| Criterion ID | Satcom technology | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| | Iridium NEXT | MEO / C-band | Inmarsat 4 (BGAN) - Inmarsat 6 (ICE) | IRIS FOC | Thuraya | GEO / S-band | GEO / C-band | GEO / X-band | SmartLNB | GEO / Ku-band | Inmarsat 5 (Global Xpress) |
| CRT-NONT-1 | PC | NC | C | NC | PC | PC | C | C | C | C | PC |
| CRT-NONT-2 | C | C | C | C | C | C | C | PC | PC | PC | PC |
| CRT-NONT-3 | C | NC | C | PC | C | C | C | C | C | C | C |
| CRT-NONT-4 | C | C | C | N/A | N/A | N/A | C | N/A | C | C | N/A |
| CRT-NONT-5 | C | C | C | N/A | N/A | N/A | C | N/A | C | C | N/A |
| CRT-NONT-6 | PC | C | PC | C | PC | PC | PC | PC | PC | PC | PC |
| CRT-NONT-7 | C | NC | PC | NC | C | C | C | C | C | C | C |

Figure 6: Non-technical and non-functional criteria compliance matrix

### 1.5.1 Cost Benefit Analysis

The cost benefit analysis conducted as part of this study estimates the full lifecycle costs and assesses the possible sources of revenue for each SATCOM GSM-R-replacement candidate. Comparable terrestrial solutions have also been included for benchmarking purposes.

Regarding the scope of the analysis, the timespan considered ranges from 2020 to 2040 and the geographic scope includes the EU's current 28 member states, plus Norway and Switzerland. The analysis is segmented at key stakeholder level (limited here to Railway Undertakings and Infrastructure Managers, and not taking into account other stakeholders who may interact with these).

#### 1.5.1.1 Costs

The methodology makes use of a top-down approach to determine the overall operational requirements, which are then translated into infrastructure and deployment requirements based on each solution's technical features. Thereafter, a unit capital expense is applied to each concept, with the annual maintenance expenditures sized likewise. Finally, the data rates required to operate the railway communications services are computed based on telecommunications performance and market-sourced service costs.

The results are presented as a "delta", where the total cost of a specific solution is compared against a baseline, by default GSM-R.

#### 1.5.1.2 Revenues

The revenues side of the analysis has only been performed for broadband solutions, since it has been assumed that only these candidates can fully support value added services. The analysis is based on traffic and demand forecasts. Based on it, the revenue model is built upon unit tariffs per user. The demand has been sized according to EUROSTAT demographic statistics.

#### 1.5.1.3 General Outlook

The results show a clear difference between narrowband and broadband SATCOM solutions, the latter expected to require significantly larger investments. Additionally, there is a clear business model differentiation between SATCOM and terrestrial pool of candidates, while SATCOM solutions offer mainly OPEX-driven models and terrestrial solutions strongly dominated by CAPEX investments.

## 1.6 MAIN FINDINGS AFTER THE ASSESSMENT

This section provides findings regarding technical, multi-technology and non-technical criteria according to the assessment carried out with the SATCOM systems listed in Table 5.

### 1.6.1 Findings regarding Technical criteria

After analysing the SATCOM solutions, the following conclusions can be drawn:

- After the technical & functional criteria assessment, the theoretical system **MEO/C-band** is the best-positioned SATCOM solution.
- Other well-positioned SATCOM solutions (although with more requirements scored as non- or partial-compliant) are GEO/L-band (*e.g.* IRIS FOC), GEO/S-band and GEO/C-band.
- The most demanding criteria for SATCOM solutions are:
  - **Availability** for critical applications
  - **Transfer delay** between SATCOM remote terminals
  - The use of **handhelds**

These conclusions have been drawn after the assessment of only SATCOM solutions (*i.e.* without considering the behaviour of gap fillers and/or additional terrestrial systems) and by taking into account data and voice applications. If **only data applications** (*i.e.* ETCS) were considered, some criteria would not be necessary (such as the use of handhelds) and some others could be easier to comply by SATCOM solutions due to the reduced data rate (such as the link availability):

- When voice applications are not considered, data rate decreases and, therefore, link availability is largely increased.
- SATCOM communications will only consist of single hop connections (between ground stations and on-board SATCOM terminals). In this way, the transfer delay is reduced compared to with that of the double hop connectivity required for user-to-user (voice) connections.
- SATCOM handhelds, the most demanding type of terminals, would therefore no longer be required.

This hypothesis makes more feasible GEO solutions operating at low frequency bands (L, S and C bands), since their main constraints are the delay on double hop connections and the absence of handhelds.

It is worth mentioning that in the long term, the concept of operation in railways could change and voice services could be replaced by data applications, making possible the use of SATCOM solutions to support services currently provided by voice and data applications using only data. In addition, in the long term, there may be a SATCOM solution complying with both voice and data services (such as the MEO/C-band solution), being also possible this way to offer a SATCOM solution compliant with all the criteria identified.

### 1.6.2 Findings regarding Multi-technology criteria

Regarding multi-technology criteria (where only the CRT-MULT-1 has been assessed), **all the SATCOM solutions evaluated are compliant**. This means that all of them are packet-switched networks, or at least part of their solution is based on packet-switched technology. In fact, some of the solutions assessed are exclusively based on a packet-switched method, and some others are both circuit-switched and packet-switched.

### 1.6.3 Findings regarding non-Technical criteria

If only safety-critical data and voice services are considered, the most competitive value proposition is that of **narrowband solutions**. In this context, SATCOM solutions such as Iridium NEXT, Inmarsat 4/6 or GEO/C-band, as well as a hypothetical MEO/C-band, would be ideally suited as GSM-R replacements compared to the existing terrestrial communications, bearing in mind that:

- Such a competitive edge is dependent on the cost of terminals.
- SATCOM's competitiveness is dependent on the need to deploy new base stations for competing terrestrial technologies, such as LTE, compared to the current GSM-R deployment, which will be able to be reused by such mobile solutions.
- A future review of functional requirements to eliminate the need for voice communications would make the position of SATCOM solutions even stronger.
- Narrowband solutions would severely hinder the growing offering of value-added services by Railway Undertakings. Nevertheless, they could prove a suitable direct successor to GSM-R.

**Broadband solutions** expand the possibility to open new markets for the rail users generating multiple sources of revenue and being able to recover the strong initial investments required to provide the service. Broadband solutions are an especially good alternative for GSM-R replacement when considering that:

- The key assets (*e.g.* antenna) of SATCOM broadband solutions are their flexibility and scalability for deployment, together with their OPEX-intensive model. This is in contrast with the necessary CAPEX needed to upgrade LTE (the main broadband terrestrial technology) from a fully functional-focused deployment to a user added value-capable system.
- As a result, SATCOM could be deployed progressively and—to a considerable degree—by sharing costs among railway undertakings, while LTE would put a high burden on infrastructure managers, requiring the full coverage deployment for specific rail lines before reaching operational capability.
- Global economic results suggest that GEO/Ka-band could provide a competitive alternative to LTE while, at the same time, leverage the above assets. Comparatively, LTE could provide either a stronger or a significantly weaker business case, depending on the need to deploy additional new-build ground stations in order to support a high frequency, high data rate solution at high speed.

From the **business point of view**, narrowband SATCOM solutions could stand as a strong option for providing safety-critical applications for rail, especially if a future maturation of requirements should segregate or eliminate the need to support voice communications together with safety-critical data. In addition, SATCOM solutions can help to introduce ERTMS on those lines where, due to the high cost of terrestrial infrastructure, it is not deployed yet.

In comparison, for such a case, and assuming a *Brownfield* scenario (*i.e.* where a current GSM-R infrastructure is deployed) a modest implementation of LTE would prove competitive against SATCOM narrowband solutions with a slightly higher cost, provided a generous re-utilisation and upgradability for current GSM-R infrastructure was carried out. For a *Greenfield* scenario (*i.e.* on a deployment from scratch where there is no infrastructure to re-use), LTE losses its competitiveness regarding SATCOM solutions, since it is required a whole infrastructure deployment along the line(s) where to provide the service.

Meanwhile, broadband solutions offer the possibility of incorporating a source of revenue that, if leveraged wisely from a commercial point of view, could lead to profitability—resulting in a very high

NPV in the long term. GEO/Ka-band offers a good competitive edge in economic terms in the same class as a moderately conservative LTE estimate.

In addition, the modularity and the OPEX-intensive economic model proposed by SATCOM solutions offer the possibility of a gradual implementation. In stark contrast, LTE implies that in general a small number of infrastructure managers should have to make strong initial investments to deploy terrestrial infrastructure, and with little room for a scaled deployment, requiring instead a comprehensive land-based infrastructure to provide initial operating capability. All this makes LTE a more financially-demanding solution compared with that of SATCOM broadband candidates.

As a result, SATCOM solutions can be implemented at a rather low and progressive initial investment in select rail services to fulfil the current demand, hence providing a solid platform to stand as either a stop-gap measure for more investment-demanding solutions, or as initial proof-of-concept and progressively ramped-up services for full-scale deployment in their own right.

## 1.7 GENERAL CONCLUSIONS AND RECOMMENDATIONS

Figure 7 shows the complete compliance matrix of technical, multi-technology and non-technical criteria for the eleven SATCOM systems evaluated. This matrix shows that all the SATCOM solutions assessed have more than one criterion not compliant plus some partial compliant, as well. It means that **there is not any SATCOM system fully compliant with current criteria identified**. This is mainly because GSM-R voice requirements become the main barrier for SATCOM, due principally to the fact that their values are out of the scope of any current SATCOM solution (in terms of availability, latency and even capacity for the whole European demand). Therefore, it is strongly recommended to reconsider such requirement's values (*i.e.* latency and availability) taking into account the **safety cases**[4] for these scenarios where SATCOM could be working standalone (*e.g.* remote/rural areas).

Having a look of the complete compliance matrix in more detail, it can be observed that:

- All the solutions are compliant with the multi-technology criterion, meaning that all of them can be integrated within a FRMCS consisting of several communications systems (*i.e.* heterogeneous technologies) and allowing the convergence of networks that would enable a multi-link scenario.
- The system technically best evaluated (the MEO/C-band solution) is also the worst evaluated non-technically. It is because of the MEO/C-band is nowadays only a theoretical solution[5].
- The IRIS FOC solution has a similar behaviour than the MEO/C-band, since its technical evaluation is highly positive (only with a bad grade on the double-hop delay). In addition, this solution is currently planned, although from 2025.

[4] It is worth mentioning that a similar situation have been considered in the **aeronautical environment**, where ATM (*Air Traffic Management*) applications requirements are classified according the **airspace domain**, such as the APT/TMA (*Airport/Terminal Manoeuvring Area*), ENR (En Route) and the ORP (Oceanic, Remote and Polar). For example, in the areas where SATCOM is the only mean of communications (*i.e.* ORP), QoS requirements (*e.g.* latency) are relaxed, and not only to make possible the use of SATCOM where no other terrestrial system is available, but also because the specific features of these domains (in terms of number of users, operations required, etc) make possible this relaxation keeping the safety case. For the contrary, in APT/TMA, it is mandatory the presence of, at least, two different links, *i.e.* multilink (LDACS/VDL2, AeroMACs).

[5] Despite the MEO/C-band is only a theoretical solution, a similar solution exists nowadays. It is a MEO/S-band (ICO), which is currently reaching its end of life.

- Some of the other systems best positioned, the GEO/C-band solution, has main problems on the double-hop delay, handhelds and security but, on the other hand, its non-technical evaluation is largely positive.

| Criterion ID | Satcom technology | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| | Iridium NEXT | MEO / C-band | Inmarsat 4 (BGAN) - Inmarsat 6 (ICE) | GEO / L-band + ANTARES CS | Thuraya | GEO / S-band | GEO / C-band | GEO / X-band | SmartLNB | GEO / Ku-band | Inmarsat 5 (Global Xpress) |
| CRT-TECH-1 | NC | C | NC | C (Low) | NC | C (Low) | C (Low) | NC | NC | NC | NC |
| CRT-TECH-2 | C (Low) | C (High) | C (Low) | C (High) | C (Low) | C (Low) | C (High) | C (High) | C (High) | C (High) | C (High) |
| CRT-TECH-3 | C | C | C | C | C | C | C | C | C | C | C |
| CRT-TECH-4a | C (High) | C (High) | NC | C (Low) | C (Low) | NC | C (Low) | C (Low) | NC | C (Low) | C (Low) |
| CRT-TECH-4b | C (High) | C (High) | NC | NC | NC | NC | NC | NC | NC | NC | NC |
| CRT-TECH-5 | C (High) | C (High) | C (Low) | C (Low) | C (Low) | C (Low) | C (Low) | C (Low) | C (Low) | C (Low) | C (Low) |
| CRT-TECH-6 | C | C | NC | C | C | C | C | C | C | C | NC |
| CRT-TECH-7 | NC | C | NC | C (High) | NC | C (High) | C | C | C (High) | C | C |
| CRT-TECH-8 | NC | C | PC | C | NC | C | C | C | C | C | C |
| CRT-TECH-9 | C | C | C | C | C | C | C | C | C | C | C |
| CRT-TECH-10 | C | C | C | C (Low) | C | PC | C | C | PC | C | C |
| CRT-TECH-11 | C | C | C | C (Low) | C (Low) | C (Low) | C | C | C | C (High) | C (High) |
| CRT-TECH-12 | NC | C | NC | C | NC | C | C | C | C | C | NC |
| CRT-TECH-13 | C | C | C | C | C | C | C | C | C | C | C |
| CRT-TECH-14 | C | C | C | C | NC | C | C | C | PC | C | C |
| CRT-TECH-15 | C (Low) | C (High) | C | C (Low) | C (Low) | C (Low) | C (High) | C (High) | C (Low) | C (High) | C (High) |
| CRT-TECH-16 | C (Low) | C (Low) | C (Low) | C (Low) | NC | C (Low) | C (High) | C | C (High) | C (High) | C (Low) |
| CRT-TECH-17 | C (Low) | C | C (Low) | PC | C (Low) | C | PC | PC | PC | PC | PC |
| CRT-TECH-18 | C (Low) | C (High) | C (High) | C (High) | C (Low) | C (High) | C (High) | C (High) | C (High) | C (High) | C (High) |
| CRT-TECH-19 | NC | NC | C | NC | NC | PC | NC | NC | PC | NC | NC |
| CRT-MULT-1 | C (Low) | C (High) | C (Low) | C | C (Low) | C | C (High) | C (High) | C | C (High) | C (High) |
| CRT-NONT-1 | PC | NC | C | NC | PC | PC | C | C | C | C | PC |
| CRT-NONT-2 | C | C | C | C | C | C | C | PC | PC | PC | PC |
| CRT-NONT-3 | C | NC | C | PC | C | C | C | C | C | C | C |
| CRT-NONT-4 | C | C | C | N/A | N/A | N/A | C | N/A | C | C | N/A |
| CRT-NONT-5 | C | C | C | N/A | N/A | N/A | C | N/A | C | C | N/A |
| CRT-NONT-6 | PC | C | PC | C | PC | PC | PC | PC | PC | PC | PC |
| CRT-NONT-7 | C | NC | PC | NC | C | C | C | C | C | C | C |

Figure 7: Complete compliance matrix

Therefore, the main conclusions that can be drawn after the assessment of all criteria are that:

- No SATCOM system being the only mean of communications is fully compliant with all the current criteria identified.
- Some of the best-positioned solutions (**existing systems** operating at lower frequency bands, such as GEO/S- or C-band) could be integrated within a FRMCS with some limitations in some of the applications to be provided.

Hence, and taking into account the possible limitations of best-positioned existing SATCOM solutions, the following **recommendations** are provided:

- Some scenarios are more propitious that others when it comes to deploying SATCOM on railways. They are the ***High Speed Lines*** and ***Regional Lines***.
- It is very important to reconsider the type of applications that should be supported by a SATCOM system, since they will limit the feasibility of the SATCOM solution. In this case, for example, if the **SATCOM system was just to provide ETCS data** (*i.e.* not considering voice services):

- Data rate would be limited, thus making it possible to provide higher availability.
- Handhelds (one of the main SATCOM limitations) would not be required anymore.
- Double-hop delays (not compliant with GEO SATCOM solutions) would not be considered anymore, since communications would take place between users (trains) and the SATCOM HUB (*i.e.* ground station).

- In (regional) lines with low traffic volumes and low-to-medium speed, it could be feasible to keep ETCS data and also voice services in exchange for relaxing some criteria (*i.e.* something similar to ERTMS regional). That would allow the use of ERTMS in those lines currently deprived of an automatic train protection and management system mainly due to economic deployment reasons.

Finally, and with the aim of clarifying some of the points detected at this study that need more analysis in order to provide a more accurate SATCOM solution for railways, or even developments or upgrades required for the SATCOM industry to provide products for railways, several **recommendation for way forward** are presented:

- To estimate accurately the **railway data traffic** demand by means of **simulations** considering both number and distribution of users, in order to be able to corroborate theoretical studies and feasibility of SATCOM solutions (mainly in terms of capacity).
- The SATCOM industry to **upgrade essential elements for SATCOM** solution in trains, such as the antenna.
- To advance in the ***smart routing*** element/functionality that will be able to perform smooth transitions between the different bearers available (including SATCOM).
- Finally, and due to the strong potential synergies and compliances detected between the aeronautical and railway domains, to analyse how the **IRIS FOC** system, which is the future SATCOM solution to provide *Air Traffic Management* applications, could be also used for the railway safety applications, although some modifications could be required.

## 2. INTRODUCTION

### 2.1 DOCUMENT PURPOSE

With the purpose of studying the feasibility of Satcom solutions for the signalling (critical) applications of the railway domain, the European Union Agency for Railways commissioned Indra Sistemas and ALG to conduct the project **ERA 2016 01 SC**, "Study on feasibility of SATCOM for railway communication".

This document is the **Final Report**, which aims to describe the work performed between June 2016 and January 2017.

The *European Union Agency for Railways* will hereafter be referred to as "the Agency".

### 2.2 CONTEXT OF THE STUDY

Communications for safety-critical railway applications have become an essential area within the railway domain, given that, under the current legal framework, new trains operate under the supervision of an Automatic Train Protection System (ETCS). These systems are critical since they provide movement authorizations and are able to stop the train by applying brakes when required (to avoid exceeding the speed limit).

GSM-R (Global System for Mobile Communications – Railway) is the current communication technology used in railways and is used as communication support for: safety-critical applications, such as data transmission between train and Radio Block Centre (RBC) for ETCS Level 2; and voice communication, such as driver transmissions, maintenance and shunting personnel, etc.

Although the use of GSM-R for new services and applications is limited due to its reduced bandwidth and the absence of high-capacity-demanding applications, the technology will have to be replaced in the future mainly motivated by GSM-R's obsolescence, which is expected around 2030, rather than changes in functional and/or performance requirements.

Wireless technology is continuously evolving and the need to replace GSM-R can be regarded as an opportunity to increase (if possible) the number of applications supported —not only safety-critical applications, but also mission-critical and even those for maintenance or passenger entertainment.

This opportunity can also be useful for separating railway safety application requirements from the communication system, to ensure that future changes to the communication system are made smoothly.

In this situation, several technologies have been postulated as a GSM-R substitute in the railway domain. Within the first phase of this migration process, several land-base and also SATCOM technologies are being studied.

Given that GSM-R is part of ERTMS, it seems unlikely that any current communication system (satellite or terrestrial) could be able to support railway voice and data applications without having to modify and upgrade the on-board equipment. The SATCOM system analysis to be performed is intended to yield indications on whether some of the current (or even future) solutions, with modifications, might be able to provide and support the railway requirements for voice and data used in the rail operation.

Unlike GSM-R, satellite systems do not need a special deployment for each railway line (except for terrestrial supports for those areas without satellite coverage like tunnels or stations). This is an attractive SATCOM feature, since:

- Costs of deployment and maintenance associated with the use of a terrestrial system in large areas do not exist with SATCOM solutions, and
- SATCOM solutions are able to cover a huge area and do not require a new deployment for each new line.

## 2.3 SCOPE AND OBJECTIVES OF THE STUDY

The main objective of this study is to provide a detailed and justified answer to the questions requested by the Agency in the ToR [RD-01]. These questions are mainly related to the feasibility of the SATCOM technology to support the IP based ETCS data and voice applications in the railway domain. However, it is not only focused on the technical aspects but also in their economic impact from cost savings and value added services point of view.

Currently, in the railway domain, one of the most important challenges is to separate the applications from the bearer technology (at present GSM-R). This is crucial in order to derive the adequate application requirements that allow defining those technologies able to meet the stringent requirements requested by the so-called safety critical railway applications.

This project aims to identify which are the most relevant technical parameters and criteria in the railway communication system that can drive the selection of the best SATCOM candidate. In addition, criteria are defined in such a way that allows performing qualitative analysis to check their feasibility.

Further, the economic viability of the proposed solutions is analysed to provide non-technical aspects that contribute to the decision regarding the feasibility of the satellite technology for railway communications.

Below are presented the questions requested by the Agency:

1) *Can unmodified (off the shelf) satcom services and products deliver solutions which can support*
    a. *voice and data applications for the following categories:*
        i. *as bearer for IP based ETCS level 2/3 data application*
        ii. *as bearer for IP based voice applications*
2) *When not or only partially: can modified off the shelf services and products deliver solutions for the above mentioned categories?*
3) *On what geographical part of the European railway network could a satcom solution be used successfully?*
4) *What are the conditions to create and implement suitable solutions?*
5) *What could be the economic impact (cost savings) of satcom solutions compared with full terrestrial solutions?*

## 2.4 STUDY METHODOLOGY

The methodology followed to complete the objectives of this study is presented in Figure 8, where the work to be performed has been broken down in four main tasks:

- ***Task 1***: Identification of the parameters and criteria (technical, multi-technology and non-technical) for the subsequent assessment of SATCOM solutions.
- ***Task 2***: Detailed analysis of the satellite communication market with respect to the candidate solutions and technology to be adopted in railway domain. This second task also includes a consultation process in order to identify the trends and manufacturers' roadmaps regarding SATCOM solutions.
- ***Task 3***: The activity in task 3 is split into three main tasks
    - Analysis of solutions and technologies regarding criteria and parameters from task 1 (*e.g.* performance, functional, technical, cost, etc)
    - Criteria assessment by using a compliance matrix with all railway communication requirements and candidate solutions.
    - Identification of the deployment and operational requirements or contour conditions.
- ***Task 4***: Drawing conclusions and recommendations taking into account the results of the previous tasks. It also provides answers to the questions requested by the Agency as a main objectives of this study. In addition, a Business Case Analysis taking into consideration the potential introduction of additional services provided by the solutions proposed (*e.g.* non-safety or mission-critical services) is performed.

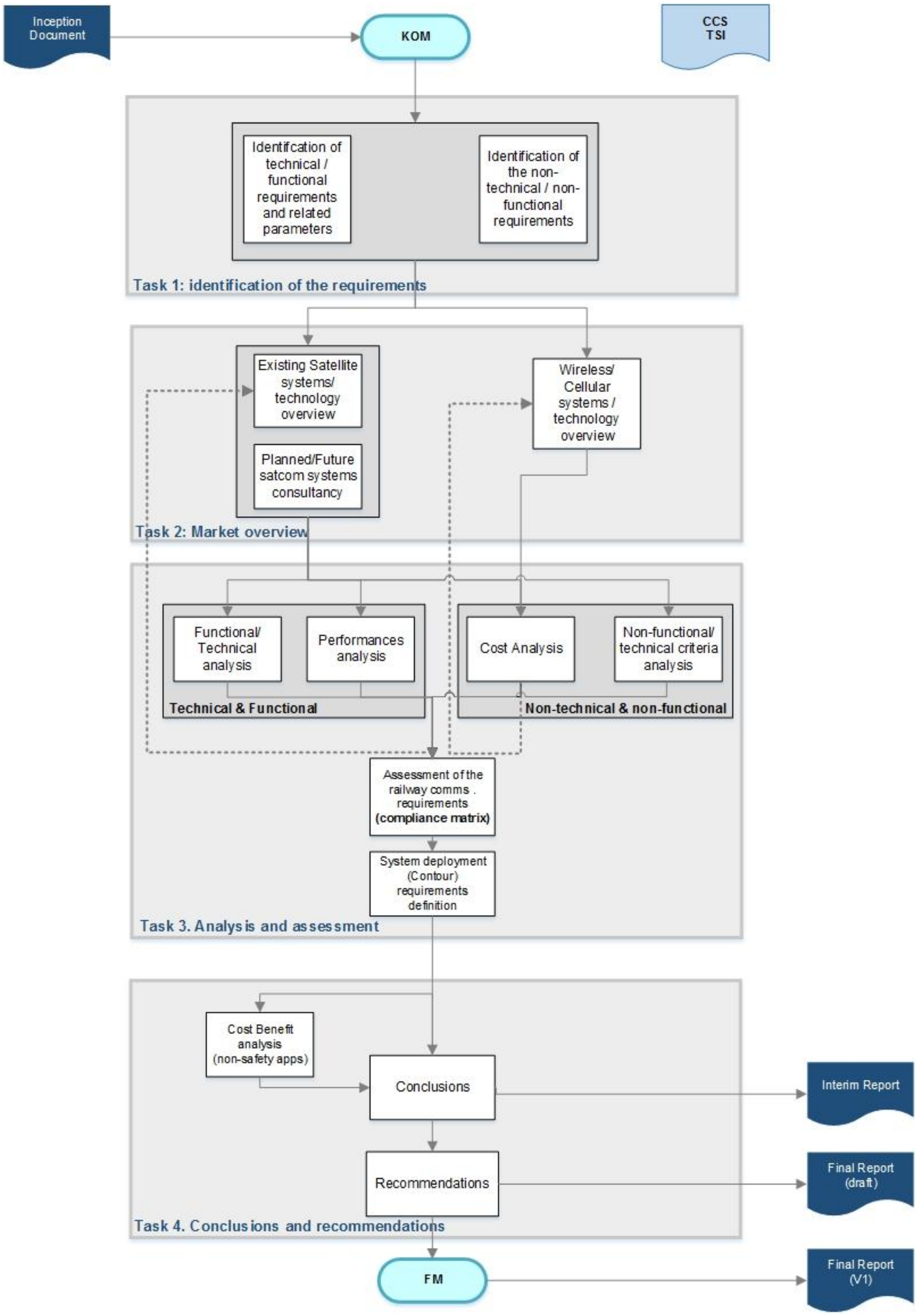


Figure 8: Study methodology

## 2.5 DOCUMENT STRUCTURE

This document is structured into the following sections:

- Section 3 provides the main results of the analysis of the railway applications described in the URS document [AD-01], a main input for this study.
- Section 4 introduces Satellite Communications Systems adapted to railway applications.
- Section 5 summarises the identified criteria to be evaluated against the proposed satellite communications systems.
- Section 6 presents the SATCOM solutions identified in the market survey.
- Section 7 lists a pre-selection of SATCOM solutions to be analysed and describes why some of the solutions identified in the market survey are discarded in advance.
- Section 8 shows the main conclusions of the consultation process carried out to the SATCOM and railway markets regarding their views about SATCOM for railways.
- Section 9 provides the assessment of SATCOM solutions based on technical, multi-technology and non-technical criteria. This section also shows the methodology followed in the cost analysis study and CBA for both SATCOM and terrestrial solutions and their delta cost regarding current GSM-R.
- Section 10 shows the operational and deployment conditions of SATCOM for railways.
- Section 11 presents the conclusions and recommendations of this study.
- Section 12 provides answers to the ToR questions.

In addition, this Final Report includes a number of annexes containing extra material:

- Annex A shows the criteria identification, including justification and traceability.
- Annex B presents the questionnaire used for the consultation process.
- Annex C provides the technical assessment of each SATCOM solution with justifications.

## 2.6 APPLICABLE DOCUMENTS

AD-01 **User Requirement Specification (URS).** FRMCS Functional Working Group. Version 2.0, 29th March 2016.

## 2.7 REFERENCE DOCUMENTS

RD-01 **ERA TOR**: Instructions to tenderers and Specifications attached to the Invitation to Tender No. ERA 2016 01 OP “Study on feasibility of satcom for railway communication”

RD-02 **SATCOM4rail**, Final report: Specification of a Certification Framework for Satellite Communication in Railway Safety Applications (ESA Contract N.: 4000107663/13/NL/CLP)

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## 3. RAILWAY APPLICATIONS

User Requirement Specification (URS) document [AD-01] summarises a set of user requirements for the FRMCS, regardless of the communication technology (*i.e.* bearer) used. These requirements are based on the applications foreseen for the FRMCS. The URS describes relevant railway applications for the future railway mobile communication system(s), their classification and key parameters from a communications point of view. A brief summary of the main features per application is listed below, which represent a key input for the subsequent identification of criteria.

Therefore, future railway communication applications have been classified into *Critical Communication Applications* (CA), *Performance Communication Applications* (PA) and *Business Communication Applications* (BA). In addition, for each one of these categories, additional *support* applications have also been defined, which provides cross services for the communication applications. Examples of applications in each category are summarised in Table 7

| ***Critical Communication Applications (CA)*** | ***Performance Communication Applications (PA)*** |
|---|---|
| ▪ On-train voice communication from driver to controller(s) and vice-versa<br>▪ Multi-train voice communication for drivers including ground users<br>▪ Trackside maintenance voice communication<br>▪ Shunting voice/data communication<br>▪ Public emergency call<br>▪ Railway emergency communication<br>▪ Automatic train control/operations communication | ▪ On-train voice communication from train staff towards ground user(s) and vice-versa<br>▪ Multi-train voice communication for drivers excluding ground users<br>▪ On-train voice communication<br>▪ Communication at stations and depots<br>▪ Wireless on-train data communication for train staff<br>▪ M&C of non-critical infrastructure<br>▪ Real time video |
| ***Business Communication Applications (BA)*** | ***Critical Support Applications (CSA)*** |
| ▪ Inviting-a-user messaging<br>▪ Emergency help point for public<br>▪ Wireless internet on-train for passengers<br>▪ Wireless internet for passengers on platforms | ▪ Secured voice/data communication<br>▪ Location services<br>▪ Authorisation of voice/data communication<br>▪ Authorisation of applications<br>▪ Prioritisation<br>▪ Multi-user talker control |
| ***Performance Support Applications (PSA)*** | ***Business Support Applications (BSA)*** |
| ▪ Information help point for public | ▪ *(No BSA defined at URS v2.0)* |

Table 7: Examples of applications defined and categorised in the URS document

Following figures show attributes' statistics of the applications classified and defined in the URS.

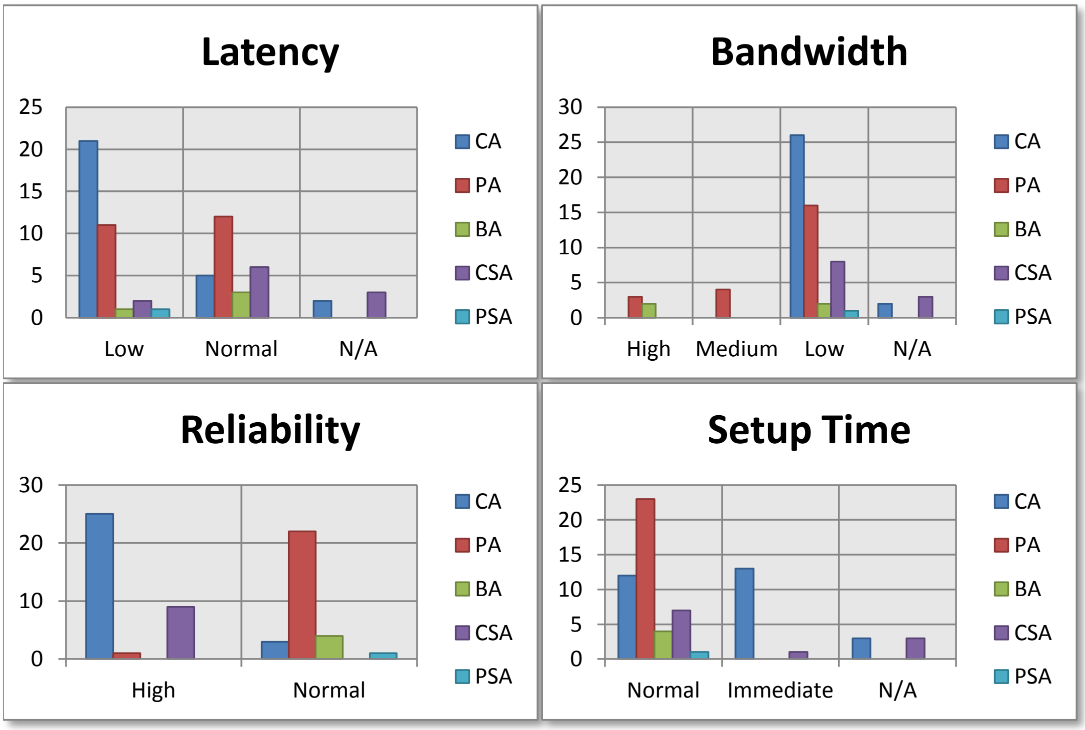



Figure 9: Railway applications for the FRMCS - communication attributes: Latency, Bandwidth, Reliability and Setup time – QoS Perfomances

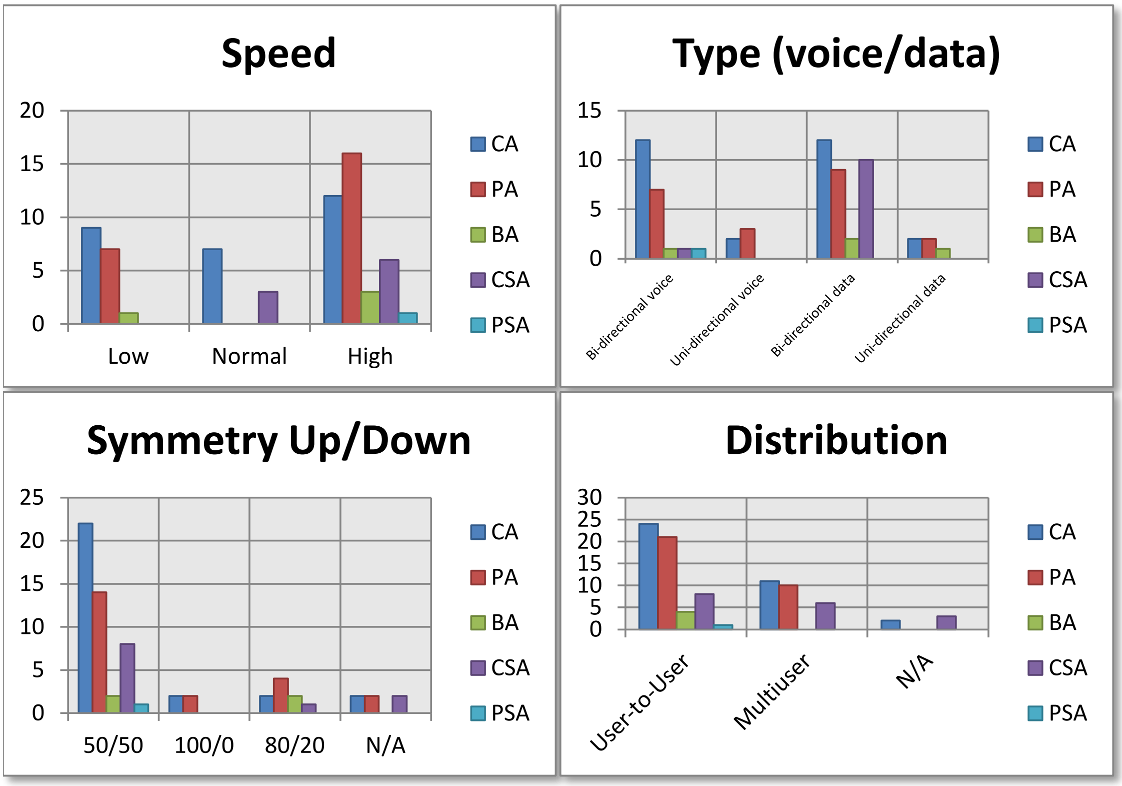



Figure 10: Railway applications for the FRMCS - communication attributes: Speed, Type, Symmetry and Distribution – System features

The main conclusions obtained from the data compiled for the critical application mentioned in the URS document are that:

- **High reliability** is required for these critical applications (in comparison to the performance and business ones).
- **Low latency** and **immediate setup** are highly demanded in most of the critical applications.
- **Voice calls shall be supported**, including user-to-user and multi-user.
- **Narrow[6] band systems** seem to be sufficient to support voice and data in critical applications.

---

[6] New future railway critical applications are being considered nowadays and could change this conclusion about narrow band systems and their ability to support the complete set of voice/data critical apps. For example, the transmission of a real-time video for ATO purposes is being discussed at present. If this application (or a similar one) is finally confirmed, this assumption will not be true.

However, it is interesting to point out that in other fields (such as the RPAS – *Remotely Piloted Aircraft System*) similar discussions have been addressed, and finally video applications have been discarded. In fact, video image processing is expected to be eventually performed on-board (thus avoiding the transmission of large amount of data through the return channel).

- **Two-way communications** (*i.e.* 50/50 symmetry) are required for most of the critical applications.

These conclusions are taken into account in the parameters and criteria identification process (detailed in section §5), since they represent a key input for this process

# 4. SATELLITE COMMUNICATION SYSTEM DESCRIPTION

## 4.1 BASELINE SATCOM SYSTEM DESCRIPTION

A satellite communications system (commonly referred to as SATCOM system) is a communication system that makes use of an artificial satellite launched into space to provide global telecommunications. A SATCOM system is mainly composed of three segments: *space segment*, *ground (or control) segment* and *user (or terminal) segment*, as can be seen in Figure 11.

### *SATELLITE PAYLOADS*

When talking about satellite communications, one important concept is the **communication payload**, which refers to the RF equipment and a set of receive and transmit antennas placed on satellites. It is important to distinguish between two main types of payload technologies: transparent and regenerative (*i.e.* On-Board Processing - OBP). Among these types, there exist several hybrid options. Transparent payload means that satellite is acting as a mirror in the space whereas regenerative payload is recovering the signal at the space segment and regenerating it again, employing the same or different waveform (*e.g.* typically DVB-RCS → DVS-S2) in order to be transmitted to the receiver station. The regenerative payload is able to remove the impairments suffered in the uplink, and in this way the link budget on the downlink is highly improved enabling the use of smaller stations/terminals. In conclusion, regenerative payloads ease the deployment of mesh networks where the delay can be reduced due to only single hop is necessary to connect two terminals.

### *SATELLITE CONSTELLATIONS*

Several **constellations** are usually used for SATCOM systems depending on the services to be offered and the required coverage. Most of these systems are based on geostationary orbits (*i.e.* GEO), which provide important advantages with respect to non-geostationary orbits (*i.e.* LEO, MEO and HEO), since ground antenna tracking is not required and with only up to 3 satellites it can provide worldwide coverage (except for polar regions). However, due to the distance from the earth surface (~36.000 Km), big delays are encountered and conversational voice services are not too much satisfactory from user QoE point of view. Furthermore, lower orbits like LEO or MEO are achieving worldwide coverage, including Polar Regions (*e.g.* Iridium, Globalstar, etc) and enabling the use of the handhelds. On the contrary, these constellations are requiring complex ground antenna tracking and in some cases inter-satellite links with regenerative payloads.

The main features of the most typical constellations are presented in the following table:

| *Features* | *GEO* | *MEO* | *LEO* |
|---|---|---|---|
| ***Height (Km)*** | *36,000* | *6,000-12,000* | *200-3000* |
| ***Time per Orbit (hr)*** | *24* | *5-12* | *1,5* |
| ***Speed (Km/hr)*** | *11,000* | *19,000* | *27,000* |
| ***Time in site of GW*** | *Always* | *2-4hrs* | *<15min* |
| ***Time delay (ms)*** | *250* | *80* | *10* |
| ***Satellites for global coverage*** | *3* | *10-12* | *50-70* |

Table 8: Satellite constellation main types and features

Other constellation type not mentioned in the above table is HEO (Highly Elliptical Orbit). This specific satellite constellation is ideal for fixed and mobile applications within high latitudes of Northern and Southern Hemisphere including both Polar Regions. The only problem is that the user terminal needs reliable antenna tracking systems and numerous Gateway Earth Stations (GES). The essential employment possibility of this orbit is to be in hybrid constellation with GEO or Medium Earth Orbit (MEO) satellite systems to provide worldwide coverage.

## *SATELLITE BEAMS*

All satellites generate **beams**, which focuses microwaves signals onto the specified portions of the earth's surface to most effectively use the limited power of their transponders. These focused signals create unique beam patterns called "footprints." The most typical footprints types are:

- Global beam footprint,
- Mobile (or regional) beam footprint or
- Spot beams

Satellites do not always support perfectly spherical coverage areas. Therefore, shaped spot beams let the operator concentrate coverage and power where required. In addition, movable antennas also let the satellite operator provide more support (traffic) to a region on demand.

An example of typical SATCOM architecture is shown in the next figure:

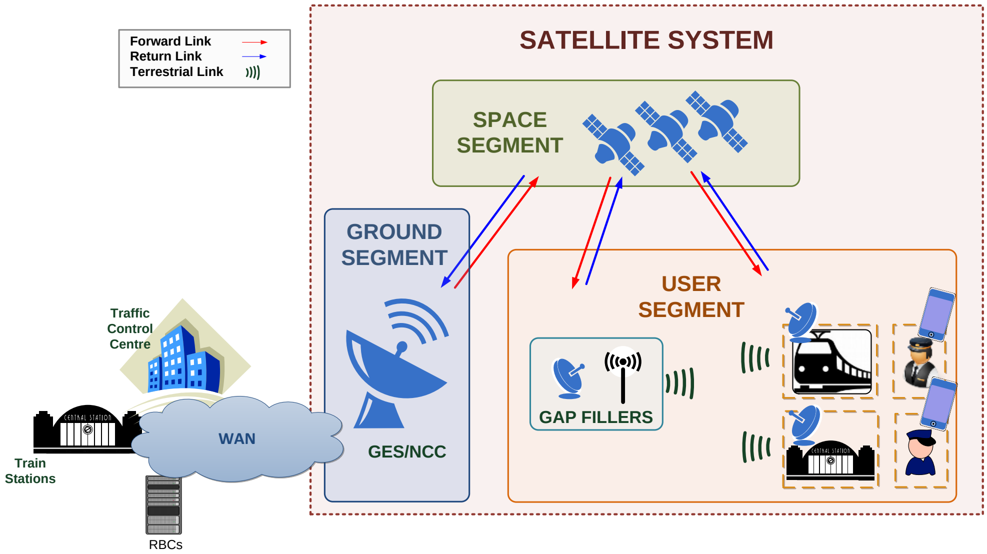



Figure 11: Satcom baseline system architecture (railway oriented)

Above figure identifies the main components of each one of the segments (*i.e.* user, ground and space) and their relationships through the satellite communication payload.

## *GAP FILLERS*

Figure 11 also shows the **gap fillers** (GF), which are the gateways (based on SATCOM terminals) in charge of resending the information received from satellite to an area without satellite visibility (and vice-versa), *i.e.* without coverage (like for example in tunnels). There are several types of gap fillers, and they can be grouped mainly in *transparent* and *non-transparent*:

- Transparent gap-fillers re-send the same satellite signal to the area without coverage. It is the best option if the satellite system has been designed to operate in a multipath environment (such as CDMA or OFDM), since the GF can be simply an amplifier of the satellite signal. It offers scarce flexibility since the whole signal on the satellite segment is re-transmitted without waveform optimization, but if the satellite signal is good enough to be retransmitted in urban areas/tunnels this solution is simpler and implies lower cost.
- However, non-transparent gap-fillers changes satellite signal to another (terrestrial) technology. This type of GF is generally used when the signal transmitted by the satellite has not been designed to operate in a multipath environment, such as TDM based. Non-transparent GF are more complex than transparent ones, but there is flexibility in the choice of the tunnel repeater technology and resource allocation, including the possibility to use a system based on OFDM modulation in order to overcome multipath. This option also implies the use of two receivers at user side (one for satellite and another one for the GF).

It is interesting to highlight that GF final coverage range will depend on the type of gap filler (transparent/non-transparent) and also on the final equipment selected and their features.

## *SATCOM TOPOLOGIES*

Two main network **topologies** are typical in SATCOM networks: *star* and *mesh*. It is shown in the next figure:

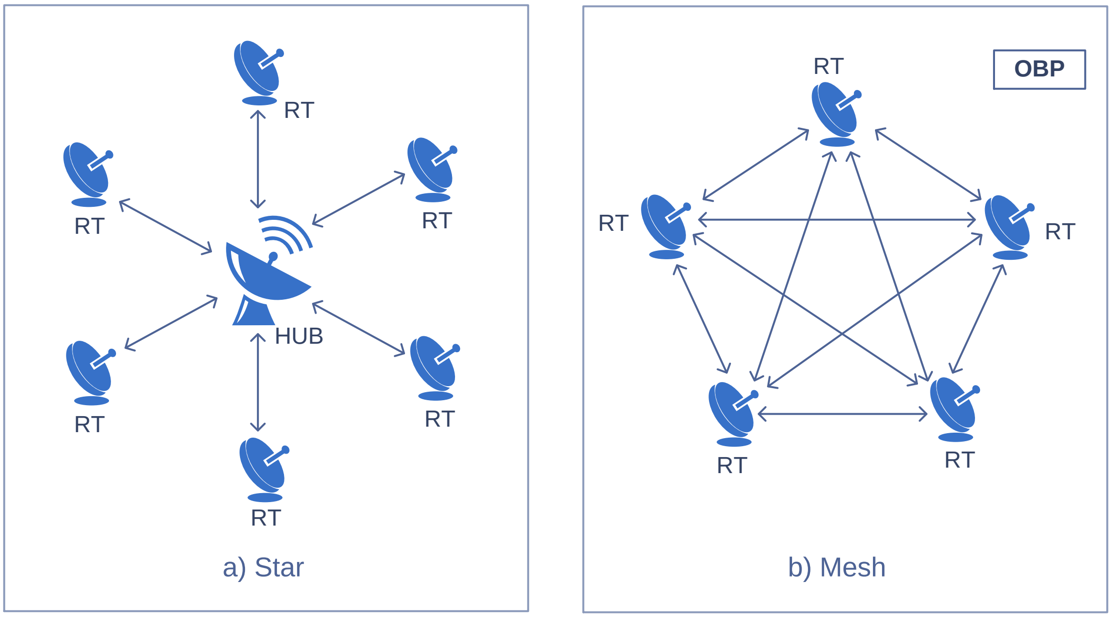



Figure 12: Satellite topologies

Star topology is the most extended topology in satellite networks, and it is characterized by having a central hub and connecting all remote terminals (RT) through this hub station. It is appropriated for broadband services. However, if it is required the connection of two remote terminals (*e.g.* voice call between remote terminals), it implies a double satellite hop (Figure 13 – a). On the contrary, in a mesh network does not exist a central node managing the communications, and all terminals are able to connect among them (*i.e.* each other) (see Figure 12-b). It means that two satellite terminals can be connected with only a single hop. The system management is distributed and in most cases one of the nodes (*i.e.* terminals) is acting as a master and taking the responsibility of the main functions of the network (*e.g.*, network reference distribution, resources management, etc.).

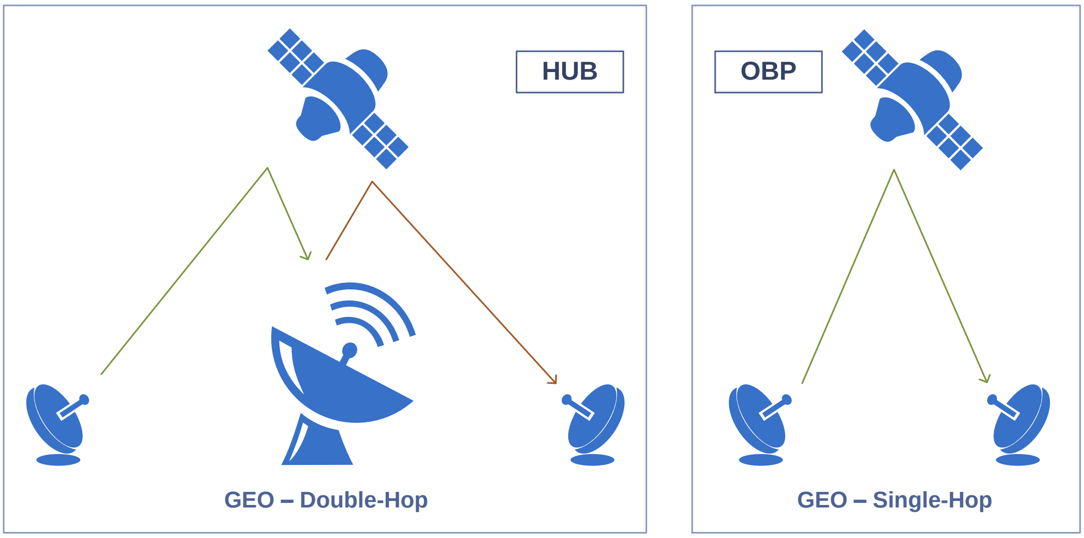



Figure 13: Satellite propagation delay. a) GEO double-hop; b) GEO single-hop

## SATCOM FREQUENCY BANDS

Since a great variety of **satellite frequency bands** that can be used exist, designations have been developed so that they can be referred to easily. The higher frequency bands typically give access to wider bandwidths, but are also more susceptible to signal degradation due to 'rain fade' (the absorption of radio signals by atmospheric rain, snow or ice). Because of satellites' increased use, number and size, congestion has become a serious issue in the lower frequency bands. New technologies are being investigated so that higher bands can be used.

Five frequency bands are used for the majority of satellite communications. The table below shows these frequencies and their allocations.

| *Frequency bands* | *Services* |
|---|---|
| **L-band (1-2 GHz)** | Mobile Satellite Services |
| **C-band (4-8 GHz)** | Fixed Satellite Services |
| **X-band (8-12 GHz)** | Military/Governmental |
| **Ku-band (12-18 GHz)** | Fixed and Broadcast Satellite Services |

| | |
|---|---|
| **Ka-band (26-40 GHz)** | Fixed and Mobile Satellite Services and Military/Governmental |

Table 9: Main SATCOM frequencies overview

For each one of the bands in the above table there are specific allocations for different regions of the world and different type of services. The specific allocations in each region may use the same or slightly different frequencies in each region. There exist allocations for SATCOM at S-band (2-4 GHz), but its use for commercial and government services is currently very limited. On the contrary, Ka-band has been majority used during the last decade for commercial services and today are still planned new deployments for offering services at this frequency band. This band designates parts where mobiles and fixed services can use the band whereas in other bands the allocation is for type of service.

An issue that has arisen in recent years for the lower frequency bands at L- and C-band is pressure from terrestrial mobile communication for part or all of those frequencies to be either transferred to terrestrial mobile use or shared between terrestrial and satellite. In some parts of the world the lower parts of C-band used for satellite communication have already been re-allocated to terrestrial use and the possibility of further re-allocations are to be discussed in the World Administrative Radio Conference. No re-allocations of L-band have been made yet but there is pressure from the terrestrial mobile communication industry for this to happen. Some S-band satellite services are due to start in Europe soon and satellite and terrestrial services will share the band.

***SATCOM ACCESS PROTOCOL***

Finally, it is worth mentioning that for most of the data communications that take place, there is a requirement for several users to share a common channel resource at the same time. For multiple users to be able to share a common resource in a managed and effective way requires some form of **access protocol** (*i.e.* Network Access) that defines when or how the sharing has to take place and the means by which messages from individual users are to be identified upon receipt. This sharing process comes to be known as multiplexing (*e.g.* TDM, FDM, CDM, etc) and multiple access in digital communications (*e.g.* TDMA, FDMA, CDMA, etc). Regarding multiple access techniques, these ones can be split between orthogonal (*i.e.* network synchronization is required) or non-orthogonal (*i.e.* asynchronous networks).

The most typical DAMA (Demand Assignment Multiple Access) techniques are based on TDMA, FDMA, CDMA or also OFDMA whereas the most popular non-orthogonal access techniques are RA (Random Access) techniques like Aloha, S-Aloha (SA), SSA (Spread-SA). Recently, enhanced RA techniques (*i.e.* E-SSA and CRDSA) have been investigated in order to be used for data applications in the field of the M2M applications, ATM communications, etc., instead of its traditional use as for network signalling (*e.g.* LOG on/off, network synchronization, etc).

### 4.1.1 Satellite communication system high-level breakdown

The general satellite system breakdown is presented below.

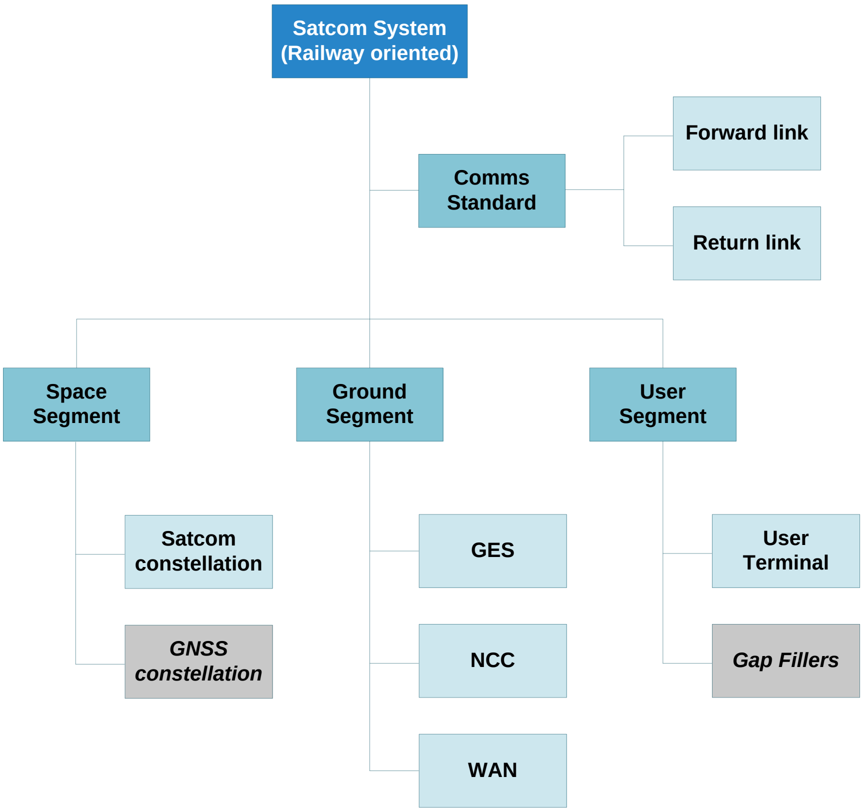



Figure 14: Baseline satellite system high level breakdown

Figure 14 shows the satellite railway architecture, which is broken down in three main segments:

- User Segment
- Ground Segment
- Space Segment

Besides, in Figure 14 a communication standard (CS) element has been included between the satellite system and its segments, because the final selection of the CS on forward and return channels can affect the selection and/or configuration of the different segments.

Below is presented a brief description of the understanding for each segment in a potential railway satellite system architecture, including also the CS.

- The **Communication Standard** defines completely the waveform to be used in both ways, forward and return channels.
  - **Forward Channel**: defines the physical layer from hub to users
  - **Return Channel**: defines the physical layer from users to hub
- **The User Segment or terminal segment** consists of the infrastructure to access satellite signals. It covers the equipment on the land, at sea or in the air, used for transmitting and receiving signals between the ground and communication satellites. These terminals access

the payload of communication satellites, which is then translated, amplified for broadcasting, and then fed to the antenna for transmission.

- **User terminals**: embarked, handheld and fixed terminals used directly by the end users (not only trains, but also staff, operation and control centres, etc.).
- **Gap filler**: gateway that transforms the satellite signal to a terrestrial signal (and vice versa) in order to provide coverage to those areas where there is not direct visibility to the satellite.

  ***Note:*** *GF is a particular element for railway scenarios due to railway channel features (like are tunnels, stations, etc). It enables the SATCOM system to be integrated with land-based communication solutions in order to provide full coverage along the trip.*

- **The Ground Segment or control segment** consists of those elements on the ground that manage the satellite resources and interfaces with the satellites (NCC and GES respectively).
  - **NCC** (Network Control Centre) is the network entity responsible for performing the satellite network control and management functions: defining frequency plans, establishing service polices, receiving reports and alarms from the network elements, and storing them to demonstrate regulation objectives fulfilment, etc.
  - **GES** (Ground Earth Station): The GES is the network entity in charge of providing communication between the service providers (RBC in the railway domain) and end users (trains, ground crew…) via satellites.
  - **The WAN** (Wide Area Network) function is to interconnect all the ground segment entities (GES, NCC) with the railway elements in charge of monitoring and controlling the whole network (RBCs, Control Centres…). WAN can be redundant in order to increase the service availability and integrity.

  Furthermore, it is also used to monitor, control and track the satellite and the payload it is carrying. Commercial SATCOM control is performed by the system owner or operator.

- **Space Segment** comprises the satellite constellation as well the launch facilities that are needed to place satellites in orbit. It is worth mentioning that it could exist more than one satellite constellation with different functionalities, such as for example one providing communications (mission critical and/or non-critical) and another one for positioning purposes.

SATCOM services can be further broken down into *fixed* versus *mobile* services. *Fixed* SATCOM services operate from a terminal on the ground at a fixed location, whereas *mobile* counterparts are transmitted from a terminal that can be in motion or temporarily stationary at the time of communication (such as a ship, aircraft or land vehicle). *Mobile* SATCOM services have traditionally provided voice and low data rate services up to about 0.5 Mb/s but, more recently, services derived from fixed satellite systems have become available offering more than 10 Mb/s.

### 4.1.2 Identification of key functional and technical SATCOM parameters

Taking into account the previous baseline SATCOM system defined, the following key functional and technical parameters are identified:

| Parameter | Definition |
|---|---|
| ***QoS / Performance*** | |
| Link availability | Percentage of time that the link is operational.<br>For satellite communication links the availability is usually expressed as a percentage of the average year. |
| Reliability | Ability of a system or component to function under stated conditions for a specified period of time. This figure is measured by means of the MTBF and MTTR values. |
| Error ratio | Probability that a data unit (bit, byte, frame, packet, etc.) transmitted through a communication link will be received incorrectly.<br>Depending on the data unit used for the error ratio calculation (*i.e.* depending on the reception stage), it can be expressed of the following way:<br>- ***BER*** (Bit Error Rate (at physical layer)) or ***FER*** (Frame Error rate (at link layer)<br>- ***PLR*** (Packet lost Rate (at IP layer))<br>The error ratio of a communication system may be affected by several factors such as interference, noise, fading, synchronization errors, etc. It can be improved acting over physical layer and/or link layer by mean of techniques such as FEC, LL-FEC, ARQ, etc.<br>The BER/FER/PLR is often expressed as a function of the Eb/N0 (energy per bit to noise power spectral density ratio). Therefore, depending on the required BER/FER/PLR for a specific service, the Eb/N0 can be calculated. |
| Transfer delay | Amount of time experienced in a transaction (one-way) due to the communication link performance.<br>Therefore, for satellite communications this parameter depends mainly on data rate and satellite constellation (*i.e.* propagation delay). |
| Delay jitter | Variation in the transfer delay of received packets. |
| Network Registration Delay | Time delay experienced by the procedure followed by a terminal to get access to the network services. Network registration procedure is also known as network *log on*. |
| Call Establishment Delay | Time delay experienced for the establishment of a voice (or data) communication session when required. |
| Capacity | Total amount of users that simultaneously is able to manage the system (*i.e.* forecast of number of simultaneous users). It allows to compute the spectral efficiency (Throughput offered / BW occupied, bps/Hz). |
| Priority / pre-emption | Capability of a communications system to prioritize calls/data flows rather than others according to their precedence level. Pre-emption is the process capable of terminating lower precedence calls when higher priority ones need such resources. |
| ***Service*** | |
| Type of service | Capability of a system to provide different types of services. These are well divided into ***Voice*** and ***Data*** services. |
| Bandwidth | Total amount of frequency band used by a system to provide service. Depending mainly on the size of this band (in terms of Hz) the system can be categorized as ***narrowband*** or ***broadband***. |

| ***Parameter*** | ***Definition*** |
|---|---|
| Types of communications | It identifies how the different users are going to interact among them, for example establishing:<br>- Point-to-point calls/sessions<br>- Point-to-multipoint calls/sessions<br>- Multi-Party calls/sessions<br>- … |
| ***System*** | |
| Coverage | Geographic area where the system is able to provide service.<br>Satellite coverage is usually communicated in the form of footprints, which display satellite G/T, EIRP or other quantity, such as the antenna size required for good quality reception of a particular service. |
| Topology | It refers to the organization of the different users in a system and how they communicate among them. For SATCOM systems, there are 2 main topologies: ***star*** and ***mesh***. |
| Constellation | Group of artificial satellites providing service for a specific SATCOM system. |
| Frequency band | Range of frequencies of the radio communication frequency spectrum.<br>For satellite systems, frequency bands used goes from L band (1-2 GHz) to Ka band (26-40 GHz).<br>Note: lower bands like VHF are currently considered for specific services with LEO constellations. |
| Mobility (*high speed support*) | Ability of a system to allow the movement of users.<br>For the railway domain, it is interesting to know not only if different technologies support mobile users, but also if they support high speed users (> 250 km/h).<br>Note: it is assumed a maximum speed of 500 km/h. |
| Flexibility | Capability of a system to respond to potential internal or external changes, in a timely and cost-effective manner.<br>One example of flexibility in a SATCOM system could be the ability of the system to add/change some physical layer parameters configurations in order to overcome some specific channel impairments. |
| Scalability | Capability of a system to react and handle large traffic load variations, regarding number of users and/or traffic per user. |
| Safety | Protection against non-intentional interference from some other users of adjacent systems (*e.g.* use of regulated/reserved frequency bands, etc) or due to the channel impairments. Countermeasures (*e.g.* FEC, CRC, Interleaving, LL-FEC etc) shall be implemented in order to assure integrity requirements.<br>Note: This parameter is only focused on mechanisms implemented at bearer level (*i.e.* at physical and link/MAC layer level) |
| Security | Protection against intentional interferences (*i.e.* such as jamming) caused by malicious users. Security mechanisms (*e.g.* encryption, authentication, TRANSEC, etc) shall be implemented in order to assure the integrity requirements.<br>Note: This parameter is only focused on mechanisms implemented at bearer level (*i.e.* at physical and link/MAC layer level) |

| ***Parameter*** | ***Definition*** |
|---|---|
| Types of terminals | Taking into account to the (SATCOM) communications system, some different types of terminals could be provided, such as:<br>- Fixed terminals<br>- Mobile terminals (*i.e.* on-board on trains - SOTM)<br>- Portable (*i.e.* nomadic)<br>- Handhelds |

Table 10: Satcom functional and technical parameters definition

### 4.2 MULTI-TECHNOLOGY COMMUNICATION ARCHITECTURE DESCRIPTION

Previous section considers the use of a SATCOM system as the only one communication system for railways. Due to its own nature, satellite visibility (coverage) is not always assured along the required area. For example, in the railway domain there are tunnels or shadowing areas due to buildings, trees… without satellite coverage. To solve this issue, gap fillers have been introduced.

But there are scenarios in the railway domain where a priori seems to fit in better a terrestrial system than a satellite one, such as for example cities, where the existence of SATCOM obstacles (buildings, stations, underground tunnels, etc), along with the high number of users and “affordable” deployments make terrestrial systems more reliable and simpler.

At this point it is worth mentioning that there are some other scenarios where a priori SATCOM system seems to be more advisable than terrestrial ones, like for example rural (remote) areas with small number of users where a terrestrial communication system deployment could be complex and too much expensive.

For that reason, and following the Next Generation Network (NGN) concept (where several access networks can be available for different types of users), future railway mobile communication architecture shall allow the coexistence of several access technologies, which will also be independent from the applications.

Figure 15 shows a complete communication architecture including both satellite and terrestrial systems in order to provide full coverage for the possible railway scenarios.

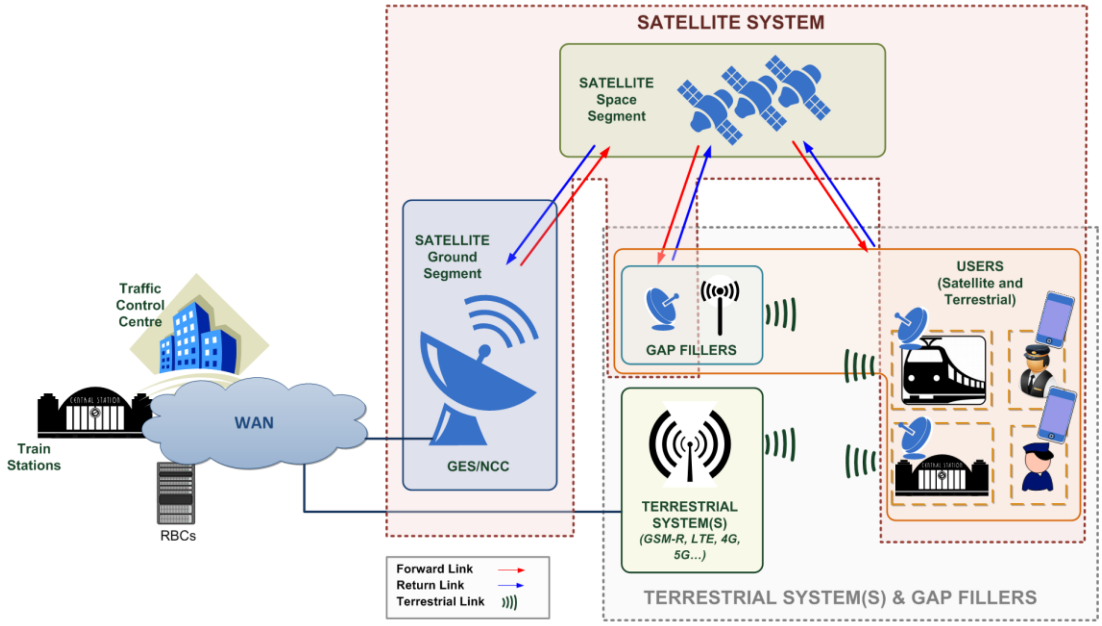



Figure 15: Railway communication architecture including SATCOM and terrestrial systems

NGN concept separates applications from transport networks (bearers). This way, from the application point of view it will not be important the selected bearer. Figure 16 shows this new concept where several bearers are available and they are used depending on the type of terminal and availability. The core transport network is based on IP and the services and applications are agnostic to the bearer.

It means that, depending on the concrete situation of each user, a terminal may need to change of bearer in order to keep its connectivity. With the aim of not disrupting the service, a smooth transition between bearers is expected, and it shall be transparent, seamless and without any action required from the user side. One important key element/mechanism within this point is the **smart-routing**, which will provide the ability of changing of communication system when required according to current availability and some other possible information like the preferred network configuration.

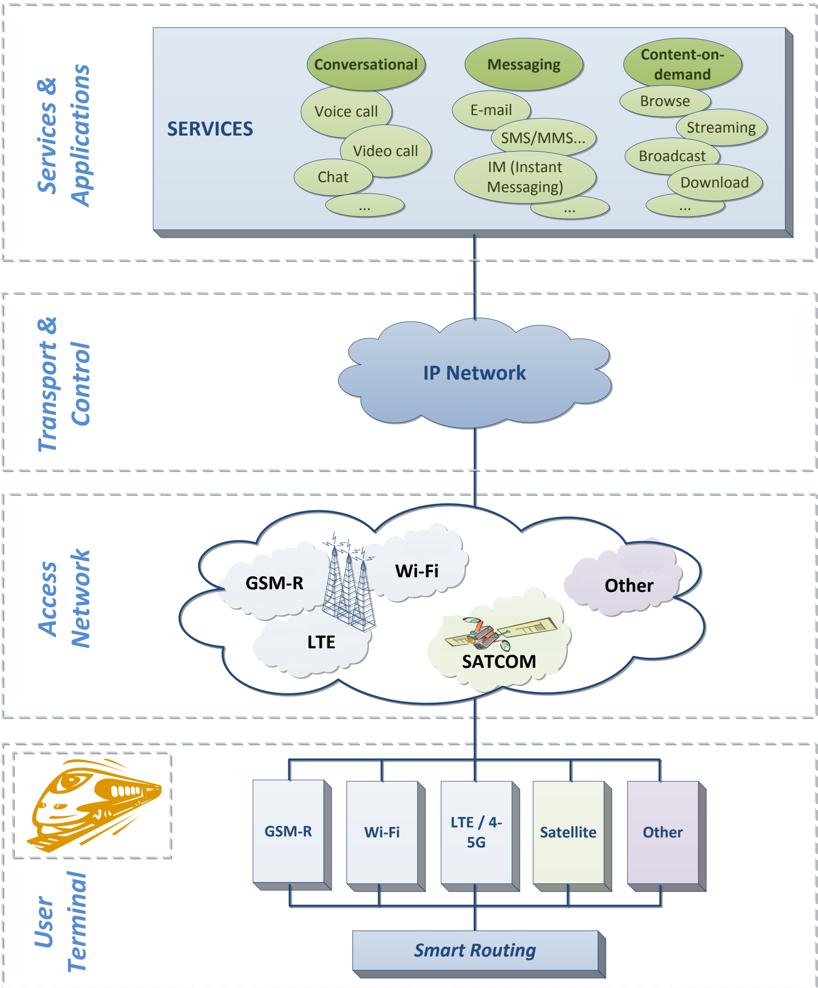



Figure 16: NGN concept applied to future railway communications architecture

The NGN architecture clearly separates the transport layer (also known as *Transport Stratum*), which includes both the access network and the core transport network, and the service layer (also known as *Service Stratum*), which is in charge of processing the signalling generated by the users when asking for a service.

At the core of the NGN architecture (within the *Service Stratum*) is the IMS (IP Multimedia Subsystem), which provides, for multimedia services, an independent access platform for a variety of access technologies, such as satellite, 3G, 4G, WiFi, cable… guaranteeing the end-to-end QoS according to user's SLA.

### 4.2.1 Identification of key parameters due to coexistence of several systems

Once the complete architecture for the future railway communications has been depicted, it can be observed that, due to the coexistence of several communication technologies (terrestrial and satellite), some new functional and technical parameters appear. They are described in Table 11:

| Parameter | Description |
|---|---|
| Packet switched network | Feature of a communication system where the information exchanged between users is performed by packets (unlike circuit-switched networks where data is exchanged by means of dedicated point-to-point connections during calls). |
| IP-based services (“All-IP”) | Characteristic of a communication network where every service provided is IP. |
| Guaranteed QoS | Capability of a communication system to guarantee the quality of service end-to-end according to user’s SLA. |
| Seamless verticals handovers | Capability of a communication system to change the service for a group of users from one communication technology to another and to be transparent from the user point of view. |
| Multi-technology terminals | Capability of a user terminal to be able to provide communications services by means of several bearers according to user’s preferences or suitability of the link. |

Table 11: Multi-technology parameters definition

## 4.3 NON-FUNCTIONAL/NON-TECHNICAL ASPECTS OF A (SATELLITE) COMMUNICATIONS SYSTEM

This section aims at proposing a set of key non-functional, non-technical parameters relative to the introduction of a new communications technology within the railway domain. Such parameters include sustainability, serviceability, costs, certification and maturity. These parameters are then developed into specific criteria for decision-making, building on current available and widely accepted benchmarks that are traced to each of the proposed criteria.

### 4.3.1 Identification of key non-functional and non-technical parameters

This section proposes and defines a set of non-functional and non-technical parameters, as seen in Table 12.

| Parameter | Description |
|---|---|
| Sustainability | A communication system’s ability to remain interoperable, capable of delivering its specified performance and capable of being maintained correctly and cost-efficiently in a continuous manner throughout its intended lifecycle. |
| Serviceability | A system’s capacity to be repaired or maintained/serviced while limiting the disruption to normal operations. |
| Costs | A system’s economic impact on the infrastructure owner(s) and operator(s), which may be divided into two main categories:<br>• CapEx: The non-recurrent investments in purchasing, installing, testing and broadly making a system ready for entry into service.<br>• OpEx: The recurrent costs that shall be regularly covered in order to ensure the system’s correct working order, including but not limited to direct running costs and maintenance<br>Since assessing system costs as an isolated category without its proper context is challenging and may result in pre-emptive or biased judgment, key considerations have been previously proposed that would undoubtedly have a direct impact on actual cost |

| Parameter | Description |
|---|---|
| | efficiency:<br>Additionally, the potential of the system to provide added value services is a factor which can be taken into account when assessing the cost-efficiency. |
| Certification | The complexity involved in achieving regulatory approval for a system's operational entry into service, entailing the abidance by all applicable mandatory standards, including but not limited to:<br>• Pre-existing applicable standards, *i.e.* whether the technology has been standardised and included in an applicable set of regulation, or instead whether the system builds on a novel technology that has not yet been standardised and included as such in an applicable set of regulation.<br>• Environmental impact, ensuring that the footprint of the system and its operational services are not detrimental to the environment through any type of pollution.<br>• Electromagnetic compatibility / interference, ensuring that the system's operation is safe from unintended interference with other communication systems.<br>• Security, ensuring that the system can cater for the adequate applicable protection methods against intended illicit interference for non-public communications.<br>• Physics, ensuring that the system's hardware, including but not limited to antennae and radome, is safe from external damage that would result in a malfunction, and is in turn not a threat itself to the outer environment.<br>The following legislation governs these and other domains for railway applications:<br>• EN 50126 Railway applications — The specification and demonstration of reliability, availability, maintainability and safety (RAMS)<br>• EN 50128 Railway applications — Communication, signalling and processing systems — Software for railway control and protection systems<br>• EN 50129 Railway applications — Communication, signalling and processing systems — Safety related electronic systems for signaling<br>• EN 50159 Railway applications — Communication, signalling and processing systems — Safety-related communication in transmission systems<br>• EN 50155 — Railways Applications — Electronic Equipment Used on Rolling Stock. |

<table>
<tr><th>Parameter</th><th>Description</th></tr>
<tr><td>Maturity</td><td>A system’s, and more broadly a technology’s readiness to enter service for operational activity, as defined by the US DoD’s universally accepted Technology Readiness Level (TRL):<br>
<table>
<tr><th>TRL</th><th>Description</th></tr>
<tr><td>1</td><td>Basic principles observed and reported</td></tr>
<tr><td>2</td><td>Technology concept and/or application formulated</td></tr>
<tr><td>3</td><td>Analytical and experimental critical function and/or characteristic proof of concept</td></tr>
<tr><td>4</td><td>Component and/or breadboard validation in laboratory environment</td></tr>
<tr><td>5</td><td>Component and/or breadboard validation in relevant environment</td></tr>
<tr><td>6</td><td>System/subsystem model or prototype demonstration in a relevant environment</td></tr>
<tr><td>7</td><td>System prototype demonstration in an operational environment</td></tr>
<tr><td>8</td><td>Actual system completed and qualified through test and demonstration</td></tr>
<tr><td>9</td><td>Actual system proven through successful mission operations</td></tr>
</table></td></tr>
</table>

Table 12: Non-technical parameters definition

# 5. IDENTIFICATION OF CRITERIA FOR THE ASSESSMENT OF SATCOM SOLUTIONS

Three types of criteria have been identified for the subsequent assessment of the SATCOM solutions proposed regarding their feasibility to support critical railway applications:

- Technical and functional criteria
- Multi-technology criteria
- Non-technical and non-functional criteria

A high-level definition similar to the one used within the URS document [AD-01] has been used in the description of the criteria identified.

Criteria definition, including a rationale and the traceability to the documentation on which is based each criterion is included in Annex §A.

The tables below summarise the criteria to be applied to the proposed SATCOM solutions.

| ***Technical and functional criteria*** | |
|---|---|
| ***Criterion ID*** | ***Criterion*** |
| **CRT-TECH-1** | The "**link availability**" of the proposed SATCOM system shall be **High**. |
| **CRT-TECH-2** | The "**reliability**" of the proposed SATCOM system shall be **High**. |
| **CRT-TECH-3** | The end-to-end **error ratio** of the proposed SATCOM system shall be **Low**.<br>*Note*: Since this criterion only considers the satellite system, the error ratio shall be measured after the last satellite communication layer (*e.g.* data link layer or L2) |
| **CRT-TECH-4** | **Transfer delay** for the proposed satellite system shall be **Low**.<br>*Note*: It refers to the end-to-end (one-way) delay due to the satellite channel. Therefore, it shall be measured from satellite transmitter to satellite receiver. |
| **CRT-TECH-5** | **Delay jitter** of the proposed SATCOM system shall be **Low**.<br>*Note*: Since this criterion refers to the one-way satellite channel jitter, it shall be measured from satellite transmitter to satellite receiver. |
| **CRT-TECH-6** | Network **registration delay** for the proposed SATCOM system shall be **Normal** (with similar values of current GSM-R system). |
| **CRT-TECH-7** | The **call establishment delay** for the proposed SATCOM system shall be **Low**.<br>*Note*: as a first reference, GSM-R establishment delays can be considered. |
| **CRT-TECH-8** | The proposed SATCOM system shall allow (at least) the estimated number of European FRMCS **users** by 2030 registered simultaneously. |
| **CRT-TECH-9** | The proposed SATCOM system shall provide **priority** and **pre-emption** mechanisms. |
| **CRT-TECH-10** | The proposed SATCOM system shall support **Data** and **Voice** services. |

| | |
|---|---|
| **CRT-TECH-11** | The proposed SATCOM system shall support as minimum Low bandwidth applications |
| **CRT-TECH-12** | The proposed SATCOM system for the FRMCS shall provide "*user-to-user*" and "*multi-user*" types of communications for both voice and data services. In addition, each communication can be bi-directional or uni-directional with any type of asymmetry between forward and return channels (when bi-directional). |
| **CRT-TECH-13** | The minimum required **coverage** of the SATCOM system shall be **Europe**. |
| **CRT-TECH-14** | The SATCOM system shall provide communications for remote terminals when stationary and when travelling at speeds up to the maximum allowable line speed or **500 km/h**, whichever is the lower. |
| **CRT-TECH-15** | The proposed SATCOM system shall be **flexible** to support (at least) new created apps in the future. |
| **CRT-TECH-16** | The proposed SATCOM system shall be highly and easily **scalable**. |
| **CRT-TECH-17** | The proposed SATCOM system shall allow the use of the following types of terminals: "*On-board (mobile)*", "*Handheld*" and "*Fixed*". |
| **CRT-TECH-18** | The proposed SATCOM system shall provide **high level of safety** in the information exchanged. |
| **CRT-TECH-19** | The proposed SATCOM system shall provide **high level of security** in the information exchanged. |

Table 13: Technical and functional criteria identified

| ***Multi-technology criteria*** | |
|---|---|
| ***Criterion ID*** | ***Criterion*** |
| **CRT-MULT-1** | All communication networks (*e.g*. SATCOM and terrestrial) of the future railway communications architecture shall be **Packet-Switched** (PS), since all the applications supported shall be **IP based**. |
| **CRT-MULT-2** | The end-to-end **QoS** of a communication call/session shall be **guaranteed** according to user's SLA. |
| **CRT-MULT-3** | **Handovers** among systems (aka vertical handovers) shall be **transparent** to users (*i.e.* seamless).<br>Note: This means that during a (voice or data) communication, if a change of communication system occurs, the communication shall continue without any disruption and additional user's action. |
| **CRT-MULT-4** | **FRMCS user terminals** shall be able to provide communications taking into account a **multi-technology** communication architecture. Therefore, terminals (or at least some type of terminals) shall support multi-technology in order to avoid having one different terminal per technology. |

Table 14: Multi-technology criteria identified

| Non-technical and non-functional criteria | |
|---|---|
| **Criterion ID** | **Criterion** |
| **CRT-NONT-1** | The proposed SATCOM system for the future railway communications architecture shall have a universally assumed sustained **lifecycle** covering the total timespan of the FRMCS without risk of obsolescence. Due to current estimates of migration from GSM-R, roll-out of the next generation systems is expected around the year 2022. Taking into account reference lifecycles of such systems, a sustainability of minimum 15 years is expected after this date. |
| **CRT-NONT-2** | The proposed SATCOM system for the future railway communications architecture shall provide for easy serviceability that has minimal impact on operations, whether it is due to scheduled or unscheduled maintenance/repair. Additionally, the system shall ensure that technical and multi-technology criteria compliance is maintained within the required limits throughout the lifetime of the assemblies. However, during preventative or corrective maintenance, the subsystem may not be able to respect the values quoted in the Basic Parameters; the maintenance rules shall ensure that safety is not prejudiced during these activities. |
| **CRT-NONT-3** | The proposed SATCOM system for the future railway communications architecture shall provide at least an **acceptable level of cost efficiency**, taking into account full lifecycle costs covering the full lifespan of the selected solution, and as long as technical and functional requirements allow for this option. |
| **CRT-NONT-4** | The proposed SATCOM system for the future railway communications architecture shall demonstrate forecasted full lifecycle costs that are, by all acceptable estimates, **not higher than those of GSM-R**. |
| **CRT-NONT-5** | The proposed SATCOM system for the future railway communications architecture shall demonstrate a forecasted full lifecycle **economic internal rate of return** (**IRR**, alternatively ERR) above the average minimum acceptable rate of return (MARR) set by the target Member States for public investments. |
| **CRT-NONT-6** | **Standards** shall be used to the extent possible to ensure interoperability of the proposed SATCOM system for the future railway communications architecture with communication systems (satellite, terrestrial and possible gap fillers). Additionally, the mandatory standards listed in this table shall be applied in the certification process:<br>• EN 50126 Railway applications — The specification and demonstration of reliability, availability, maintainability and safety (RAMS)<br>• EN 50128 Railway applications — Communication, signalling and processing systems — Software for railway control and protection systems<br>• EN 50129 Railway applications — Communication, signalling and processing systems — Safety related electronic systems for signaling<br>• EN 50159 Railway applications — Communication, signalling and processing systems — Safety-related communication in transmission systems |
| **CRT-NONT-7** | The proposed SATCOM system for the future railway communications architecture shall hold at least a universally accepted **technology readiness level (TRL) of 7 or above**. |

Table 15: Non-technical and non-functional criteria identified

# 6. SATCOM MARKET SURVEY

## 6.1 INTRODUCTION TO SATCOM SOLUTIONS

Nowadays, there are several SATCOM solutions providing service (voice, data, TV, M2M, backhaul of other services like 2G/3G, etc) to different types of applications and markets (media, transport, cargo, military, energy, etc). And depending on the final application or market, different SATCOM solutions fit in better than others, according, for example, to the data rate provided, the possibility of using handhelds, mobility, type of antenna required, etc, etc.

With the aim to provide a broad view of the different SATCOM systems and their adaptability to the railway domain, the market survey takes into account several solutions with different values regarding key architectural aspects/parameters of satellite communications. These "key architectural aspects" that characterise the SATCOM solution are:

- **Satellite orbit**. This aspect determines, among other factors: the propagation delay, the use of some types of terminals (*e.g.* like handhelds) and has an impact on the complexity of solutions—not only for the space segment, but also ground and user segments, since the satellite orbit determines, for example, if certain types of antennas (directive, omnidirectional) can or cannot be enabled.
- **Frequency band**. This is an important system parameter, since final features of the solution, such as the bandwidth available or atmospheric signal degradation, depends directly on the frequency band selected. In this sense, for example, higher frequency bands give access to broader bandwidths. However, they are also more susceptible to signal degradation due to rain fade (the absorption of radio signals by atmospheric rain, snow or ice). Figure 17 summarises SATCOM frequency bands and their main capabilities.

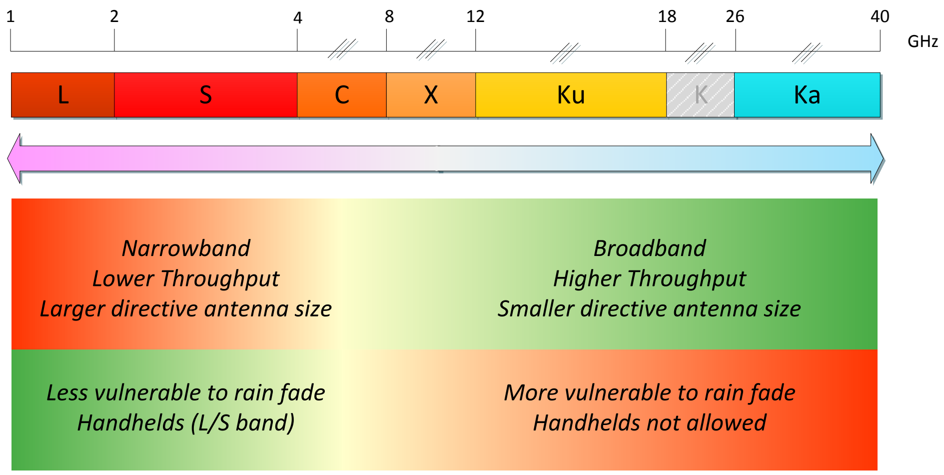



Figure 17: SATCOM frequency bands and main capabilities

- **Signal waveform / Air interface**. This is an essential aspect of the system's performance, since the modulation, codification and the different features implemented within the satellite signal are key parameters to counteract fast fading of the railway channel caused by the existence of catenaries, power arches, shadowing, etc.

## 6.2 SURVEY OF SATCOM SOLUTIONS AND TECHNOLOGIES

Since the FRMCS expects to start new communications systems deployments around 2023 and with a lifetime cycle of at least 15 years, most of the current solutions should be discarded. However, some of the solutions existing nowadays are also going to be described and analysed as future options for railways since current systems are expected to have continuity along time with new satellites/equipments replacements and even with technology improvements.

Figure 18 shows most relevant current, underway, planned and even one theoretical[7] SATCOM solutions, differentiated by orbit (LEO, MEO and GEO) and frequency band (from L-band to Ka-band).

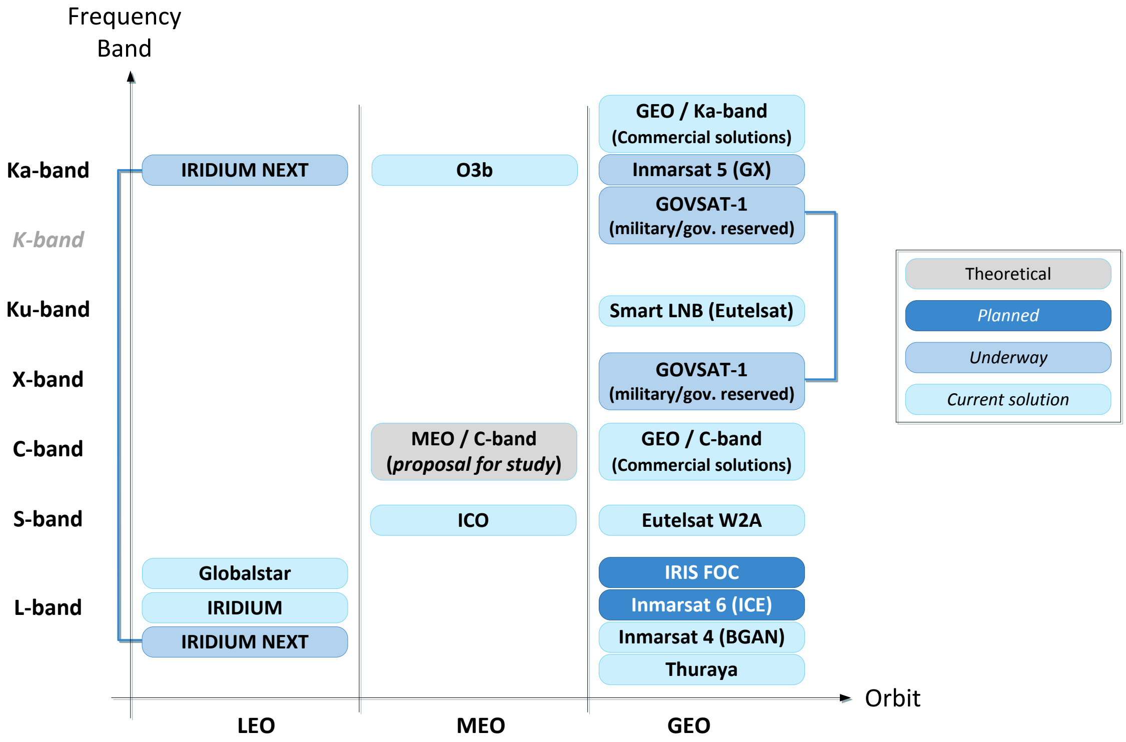



Figure 18: Current, mid and long-term SATCOM systems solutions

It can be observed at Figure 18 that GEO is the orbit most used for SATCOM systems. This is probably due to the fact that GEO satellites offer good coverage with a solution not as complex as LEO and MEO orbits. Actually, a SATCOM solution based on GEO satellites is capable to provide worldwide coverage (except for pole regions) with a space segment of only 3 satellites. Ground segment is also simpler since GEO satellites remain in a fixed position from Earth point of view, making possible this way to simplify Gateways and their pointing mechanisms to satellites.

[7] The theoretical solution is based on the **MEO/C-band** solution proposed in the **Satcom4Rail** project [RD-02],within the scope of ESA Artes 1 program.

On the contrary, and because of the distance between GEO satellites and remote terminals (about 36,000 km), transmission delay provided by SATCOM systems based on GEO constellations are never less than ~250ms (one way).

Figure 18 shows that LEO and MEO orbits are also used. Their higher complexity has probably limited their use for communications (although not for other services such as navigation, which are using MEO orbits).

However, LEO and MEO satellite constellations provide several interesting features that can be important in order to fulfil requirements for safety critical applications, such as:

- Less satellite distance with regards to terminals than GEO. LEO satellites altitude is between 160 km and 2,000 km; and MEO satellites altitude is between 5,000 and 20,000 km. Therefore, these orbits can provide advantages (regarding GEO satellites) in terms of latency and power, making possible the use of simpler terminals.
- Given that LEO and MEO solutions are formed by satellite constellations, elevation angles can be improved reducing this way the multipath effects.

It is also usual that one SATCOM solution provides services in more than one frequency band. This is the case, for example, of Iridium NEXT and GovSat-1. The first one uses L-band for mobile services and Ka-band for fixed terminals. GovSat-1 will use X-band and Ka-band, taking advantage of both ranges of frequency reserved for military and governmental services.

It is worth to notice that, regarding the SATCOM solutions depicted in Figure 18, some of them refer to “closed” solutions (*i.e.* systems where the owner provides the solution and also offers the service). Some other solutions refer to “open” solutions (*i.e.* those generic solutions where the satellite capacity can be rent to a satellite operator in order to provide the service taking advantage of commercial equipments). Both types of solutions are considered in this study.

Following subsections explain main features of each one of these SATCOM solutions. In addition, it is also included a description of SATCOM access schemes and main SATCOM communication protocols.

### 6.2.1 Iridium NEXT

#### 6.2.1.1 System Overview

Iridium Next is the next-generation satellite constellation that is going to replace the original Iridium constellation. This new constellation will also have 66 operational satellites at 780 km from the Earth’s surface (just like former Iridium) and will provide full coverage of the Earth, including oceans and Polar Regions. It will offer reliable voice and data services to and from remote areas where no other form of communication is available. Its strongest point will continue being clearly its global coverage, and now providing more bandwidth with IP-based services.

Iridium NEXT will provide high data rates up to 1.5 Mbps downlink – 512kbps uplink in L-band, and up to 8Mbps in Ka-band (fixed terminals), offering also new types of services. This way, and once NEXT is up and in operation, the new higher data rates are expected to expand the use of Iridium services in several areas such as:

- Aviation

- Maritime
- Transportation
- Government and military
- Oil and gas
- Emergency response
- Hosted payloads
- etc

But main priority of Iridium is to ensure a smooth transition to Iridium NEXT, doing an incremental one-for-one replacement of current satellites with Iridium NEXT satellites. This way, devices and services on network before Iridium NEXT launches are planned to continue working. This compatibility implies to maintain current L-band services, including the circuit-switched voice at 2.4 kbps.

The first NEXT satellites are expected to be launched as of January 2017, as soon as SpaceX (the company in charge of launching NEXT satellites) has solved problems related with an anomaly on their launching process.

#### 6.2.1.2 Iridium architecture

Iridium and Iridium NEXT share the same network architecture, which involves intelligent satellites with on board switching technology. It means that each satellite keeps inter-satellite links (ISL's) with other satellites (in fact with other 4 satellites). This way, when the satellite directly providing connectivity to the mobile user does not have a land station in its visibility (beam spot), it can route the call through multiple satellite hops to the nearest gateway, which eventually completes the call to its destination. Similar routing technique is used for mobile-to-mobile voice calls where the signal hops over multiple satellites and is down-linked directly to the mobile receiver. Each satellite maintains a routing table (analogous to routing in terrestrial networks) and uses a proprietary dynamic routing protocol to route/switch calls. Since Iridium implements this type of architecture, it can provide global coverage with fewer numbers of gateways. But as a compensation, the satellites need steerable antennas to maintain ISLs besides other complex features. Though a single gateway would theoretically provide global coverage, former Iridium has 13 gateways located in US, Italy, India and other countries for ease of management, reliability and other technical reasons.

Figure 19 shows Iridium/NEXT architecture (with a railway environment example), where the use of more than one satellite is observed when the satellite used is not able to reach a gateway. Therefore, the pass of information through ISL is required.

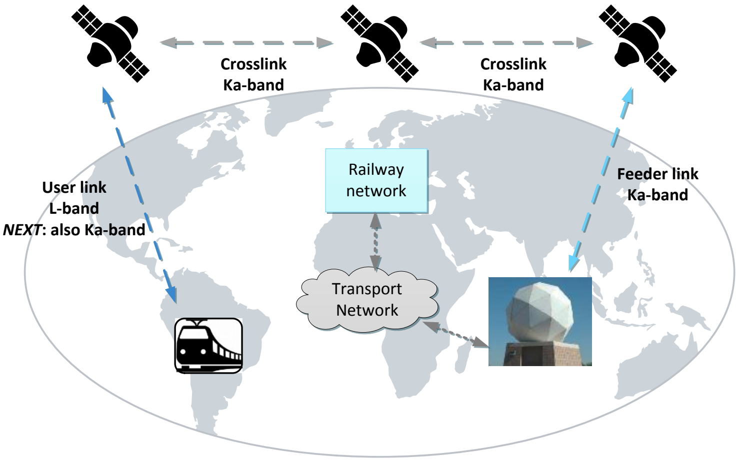



Figure 19: Iridium/NEXT architecture

Figure 19 also shows the use of different frequency bands used depending on the type of link:

- Mobile/User link:
    - L-band (1616 to 1626.5 MHz): connections between satellites and terminals
    - NEXT also uses Ka band for user link. This band allows fixed terminals throughputs up to 8 Mbps
- Feeder link:
    - Ka-band (19.4 to 19.6 GHz and 29.1 to 29.3 GHz): links between satellites and ground stations
- Inter Satellite link (ISL):
    - Ka-band (22.55 to 23.55 GHz): communications between Iridium/NEXT satellites

6.2.1.2.1 Space segment

Iridium Next will also consist of 66 operational satellites (just like former Iridium) and 6 in-orbit spares, plus an additional 9 ground spares. Therefore, a total of 81 satellites will be built. These satellites will replace current ones being fully backward compatible and incorporating new features such as data transmission which were not emphasized in the original design.

Each new satellite employs an L-band phased array antenna for the generation of 48-beam (a 4,700 km diameter cellular pattern on the Earth's surface for communication with users). As it has been explained, Ka-band links are also provided for different uses, such as user communications (fixed terminals), communications with ground-based gateways and for crosslinks with adjacent spacecraft in orbit.

NEXT satellites have an expected lifetime of 15 years.

#### 6.2.1.2.2 Ground segment

Iridium/Iridium NEXT ground segment consists of the System Control Segment (control and management of the space segment: satellite tracking, telemetry, etc) and Iridium Gateways, which interface with terrestrial networks.

The Iridium NEXT gateways provide call processing and control activities such as subscriber validation and access to control for all calls. These gateways will connects Iridium NEXT satellite network to both packet-switched and circuit-switched terrestrial networks (since in order to keep current Iridium compatibility NEXT will have also circuit-switched implementation); it communicates via the ground-based antennas with the gateway feeder link antennas on the satellite.

#### 6.2.1.2.3 User segment

Current Iridium communications system offers several types of user terminals, and since Iridium NEXT has been designed to be backward compatible, it will offer, at least, the same type of terminals:

- Handhelds
- Cab-radio (currently designed for aviation)
- Fixed terminals

#### 6.2.1.2.4 System capacity

According to [RD-03], former Iridium system has a system capacity of 80 simultaneous users in each of its 2150 active cells, for a total network capacity of 172,000 simultaneous users. The same study specifies that each satellite have a coverage area of approximately 15,299,900 $km^2$. This way, and taking into account that each satellite provides 48 cells (beams), each beam covers an area of approximately:

$$Area\ covered\ by\ one\ cell = \frac{15{,}299{,}900\ km^2\ per\ satellite}{48\ cells\ per\ satellite} = 318{,}748\ km^2\ per\ cell$$

Hence, the maximum number of users that can be co-located at former Iridium is 80 in an area of about 318 km radius.

It is assumed that Iridium NEXT will improve this capacity, adding more users for its packet-switched services. But this information is not available.

#### 6.2.1.2.5 Services

Former Iridium is a Circuit Switch system. This way, and in order to be backward compatible with current Iridium Communications System services, NEXT will keep low data rate legacy voice and data services at 2.4 kbps. However, market demands require NEXT to offer a set of higher performance services to meet customer needs, as long as IP-based services.

The Iridium Communications System customer base is widely diverse and geographically dispersed. The same satellite that may provide a substantial amount of short burst packet data service over North America may need to transition to a higher proportion of circuit switched, voice and broadband services over international waters. This capability is also essential to achieve maximum utilization of the NEXT network. The nature of the NEXT customer base will require the ability to dynamically assign power and bandwidth of system to meet the specific needs of mission critical applications over different parts of the globe. This is a fundamental principle of the NEXT system.

#### 6.2.1.3 Air interfaces

Iridium and Iridium NEXT use proprietary signal waveforms with an access scheme based on a combination of TDMA and FDMA along with frequency reuse to maximize the capacity of the system.

Each new satellite employs an L-band transmit/receive phased array antenna for the generation of 48-beam (a 4,700 km diameter cellular pattern on the Earth's surface for communication with users). Ka-band links are also provided for:

- Fixed user communications (only NEXT)
- Communications with ground-based gateways
- Crosslinks with adjacent spacecraft in orbit (just like the original system). The cross-linked 66 satellite constellation forms a global network in space allowing communications from a ground or airborne user from any location on Earth to virtually anywhere else on Earth

### 6.2.2 Globalstar

#### 6.2.2.1 System overview

Globalstar is a Low Earth Orbit (LEO) satellite constellation that originally consisted of 48 in-orbit satellites in 8 orbit planes (with 6 satellites per plane) inclined at 52º and at an altitude of 1414 km. This low altitude assures, in addition to a low latency of approximately 60 ms, a quasi-worldwide coverage (poles are not included). This first generation of satellites entered in operation in 1999, taking advantage of L and S bands to provide service to users. After several problems with some S-band amplifiers of several satellites (which offer duplex services), Globalstar decided to launch 8 more first generation satellites in 2007 to substitute premature satellite loses. In addition, between 2010 and 2013 Globalstar launched 24 new second generation satellites to form a 32 satellite constellation jointly with the 8 launched in 2007. This renewed constellation combined with the also next-generation ground network provides enhanced services with data speeds of up to 256 kbps in a flexible configuration, which means an important upgrade regarding the first generation system, which was able to provide up to 9.6 kbps. On the contrary, the use of fewer satellites implies a coverage decrease.

#### 6.2.2.2 Air interface

Globalstar takes advantage of Code Division Multiple Access (CDMA), which avoids outages caused by blockage of signals by using diversity signals from 2 satellites. CDMA provides frequency reuse by using orthogonal codes in the 1.23 MHz channels.

#### 6.2.2.3 Gateways

Unlike Iridium, Globalstar satellites do not provide ISL (Inter-Satellite Links), which means that lots of Gateways distributed around the world are required. Each gateway consists of 3 or 4 dish antennas (of around 6 meters of diameter), a switching station and remote operating controls.

Figure 20: Globalstar gateway antenna

In order to provide access, security, and roaming and billing services to users, all Globalstar gateways have a *Home Location Register* (HLR) and a *Visitor Location Register* (VLR) databases.

#### 6.2.2.4 Remote terminals

Regarding Globalstar remote terminals, there exist both, one-mode and two-mode terminals. The one-mode terminal operates only over the Globalstar system, and the two-mode terminal is able to operate on both the Globalstar system and one terrestrial system. In Globalstar operation, terminals implement a three-channel rake receiver so that they can receive signals from more than one satellite simultaneously.

The basic remote terminal is a handheld unit, similar to a terrestrial cellular mobile phone (although with a longer antenna).

### 6.2.3 ICO

#### 6.2.3.1 System overview

ICO (which name comes from *Intermediate Circular Orbit*) is a Medium Earth Orbit (MEO) satellite constellation that consists of 12 satellites (10 operational plus 2 spares) in 2 inclined orbit planes at an altitude of 10,355 km above the earth's surface. It is in operation since 2000.

Initially, the ICO system was designed for a global mobile voice telephony services, structured around the reuse of GSM technology for the ground infrastructure, since expected services were GSM-like circuit switched services. However, this design was changed during satellite production phase in order to provide both circuit and packet switched services.

Circuit switched services are:

- Voice at 4.8 kbps (basic voice)
- Enhanced voice service at variable rate

- Data and fax at 2.4 kbps
- SMS

The packet core network offers packet switched data services at data rates in the range of 6 – 28 kbps in the return link, and 20 – 144 kbps in the forward link.

#### 6.2.3.2 Air interface

ICO air interface is based on MF-TDMA access method. The modulation used in the return link is GMSK, and QPSK/BPSK in the forward link, with a channelization of 150 kHz.

#### 6.2.3.3 Satellites

Each satellite has integrated C-band and S-band payloads, where the C-band is used for feeder links, and the S-band for user links. These payloads provide the capacity to handle 4,500 simultaneous phone calls through its 163 S-band spot beams over 30 MHz of bandwidth.

Since each satellite provides a coverage of approximately 30% of the earth's surface, remote terminals can have direct visibility to more than one satellite, providing this way **path diversity**, which reduces the effect of fading and shadowing. This path diversity also allows the use of a soft-handover[8] procedure, which will be able to change of satellite before losing visibility with the previous one.

Satellites are controlled and have access to the terrestrial networks by means of the *Satellite Access Nodes* (SAN).

Figure 21: ICO F1 satellite

#### 6.2.3.4 Ground segment

ICO ground segment infrastructure consists of 11 Satellite Access Nodes (SAN) distributed around the world. The minimum number required of SANs is 7, but it is used a greater number (11) in order to improve system reliability. Each SAN is composed (among others) of 5 C-band tracking antennas,

[8] Types of handover supported by ICO system: between beams of the same satellite, between beams of different satellites and also between Satellite Access Networks (SAN).

packet and circuit switching cores and the databases required for mobility and security management (such as the VLR and HLR). The SANs are interconnected between them to form the ICONET[9].

Main elements of SANs are:

- 5 antennas
- Gateways that connect ICO network with external networks
- Packet and circuit switched nodes to correctly route traffic on the ICONET
- Databases to provide mobility and security...

#### 6.2.3.5 Remote terminals

ICO provides several types of terminals, including handhelds and specialized terminals (such as those ones for vehicles).

### 6.2.4 MEO C-band

#### 6.2.4.1 System Overview

This MEO SATCOM solution operating in C-band described within this section is not an underway or planned system. However, it is kept within this study since it was the most suitable candidate of the Satcom4Rail study [RD-02], due to its good behaviour expected within the railway domain.

The main features of this system are summarised below:

- Reduction of transmission delay and power regarding GEO satellites
- Less complex solution than LEO systems (*e.g.* lower number and speed of satellites)
- Although this solution requires several satellites, elevation angles can be improved regarding GEO solutions reducing in this way multipath effects.
- C-band has more bandwidth available than other low frequency bands like L or S.
- C-band requires larger satellite directive antennas than higher frequency bands (*e.g.* Ku and Ka). However, it is also considered the use of omni-directive antenna in the remote terminals when only providing narrow-band services

This SATCOM system under study is a long-term solution which implementation is not planned at this moment. Therefore, this solution is described within this section and it will be evaluated against SATCOM criteria (if considered appropriate), but considering that its deployment is not assured at all.

At this point it is worth to mention that, currently, a similar solution (a MEO/S-band solution - ICO) is implemented and in operation, although it is arriving to its end of live (see section §6.2.3 for more information). It means that, technically, the solution is feasible and deployable.

[9] The ICONET is the the name used to refer to the ICO network, which consists of the SANs, the links between them and the mobility databases (*i.e.* the HLR (*Home Location Register*) and VLR (*Visitor Location Register*) using the GSM terminology)

#### 6.2.4.2 System architecture

This MEO solution is based in a constellation of satellites, even when only a limited coverage area is needed. This is because only GEO satellites (located at ~36000 km from Earth surface) rotate at the same speed than Earth, revolving in a circular orbit at a constant speed of once per day over the equator.

Since the satellite footprint decreases in size as the orbit gets lower, MEO (and also LEO) systems require larger constellations than GEO satellites in order to achieve global coverage. To provide global communications with a MEO satellite system it is estimated that (at least) a constellation of 10-15 satellites are required.

Regarding the system architecture, several design aspects that shall be considered in a MEO constellation are explained in Table 16:

| | |
|---|---|
| ***Altitude*** | Usually around 5,000 – 20,000 km, although MEO is considered the region space above LEO (~2,000 km) and below GEO (~36,000 km). |
| ***Visibility*** | Very good satellite visibility, augmented by the use of satellite diversity techniques. |
| ***Coverage*** | It depends on the orbits design and number of satellites used. |
| ***Latency*** | Low latency compared with GEO satellites. Final values of latency will depend on the orbit radius, but it could be around 130 ms (for example, current O3B system, with an orbit of 8,000 km, has a roundtrip delay of 120 ms |
| ***Complexity*** | Since satellites are not in a fixed location from the Earth point of view, additional complexity to GEO constellations is added for management, satellite handovers (and seamless continuity when it occurs), etc. |
| ***Capacity*** | It depends on the frequency band (the higher the band the higher the bandwidth) and the techniques used to take advantage of it such as frequency reused. |
| ***Routing*** | In LEO and MEO constellations where satellites are in movement from the Earth point of view, how to connect satellites with ground segment shall be considered:<br>- Using a minimum number of GES assuring that each satellite always has a visible GES<br>- Using Inter-Satellite Links (ISL)<br><br>In a LEO constellation, where the number of satellites is bigger with reduced coverage areas, the best option is to implement ISLs among satellites in order to reduce the number of GES around the Earth (it is the case of Iridium).<br><br>But in a MEO constellation, where the number of satellites can be reduced considerably, it is possible to design a satellite network around the Earth with a reasonable number of GES, avoiding this way the implementation of ISL. |

| | |
|---|---|
| ***Handovers*** | Given that the MEO architecture implies satellites movement from the Earth point of view, and the railway scenario implies mobile terminals, too, the number of possible types of handover to take into account increases:<br><br>- *Beam handover* (intra-satellite HO)<br>    - In a multi-beam satellite network, beam handover occurs when the terminal moves from a beam area to another. Beam handover can be used, for example, for load balancing or service quality purposes.<br>    - Beam handover is essentially a transponder change and typically entails both forward and return links.<br>- *Satellite handover* (Inter-satellite HO)<br>    - In a satellite constellation where there are more than one satellite providing coverage, satellite handovers occur when a terminal moves from a current beam to another one that belongs to a different satellite. A satellite handover always entails a beam handover.<br>- *GES handover*<br>    - A satellite constellation may include more than one ground station (GES), even when using ISL. And in this case, when a beam handover occurs, the new beam could be associated with a different ground station than the current one. Therefore, a GES handover need also to be considered.<br>    - In the same way that previous situations, a GES handover always entails a beam handover.<br>- *Intersystem handover* (vertical handover)<br>    - Considering that a whole communication architecture does not consist only of a satellite system, but also by a terrestrial system (as it occurs in the architectures presented in this document), a vertical handover between systems shall also be considered. |

Table 16: MEO architecture main design aspects to be considered

### 6.2.5 O3b (MEO Ka-band)

#### 6.2.5.1 System Overview

Currently there is a MEO/Ka-band system providing broadband service. It is the O3b system, which despite it is not able to provide service to the whole European area, it is analysed within this study in order to analyse key features and performances of a system with these characteristics. Subsequently, conclusions will be derived to a similar solution providing coverage to the whole European area.

#### 6.2.5.2 System architecture

The O3b system offers broadband services with a MEO constellation of 12 satellites in Ka-band. Since the O3b constellation has been design to use only one Equatorial orbit 8000 km above the sea level, it provides continuous service to all parts of the Earth within 45 degrees of the Equator (see Figure 22).

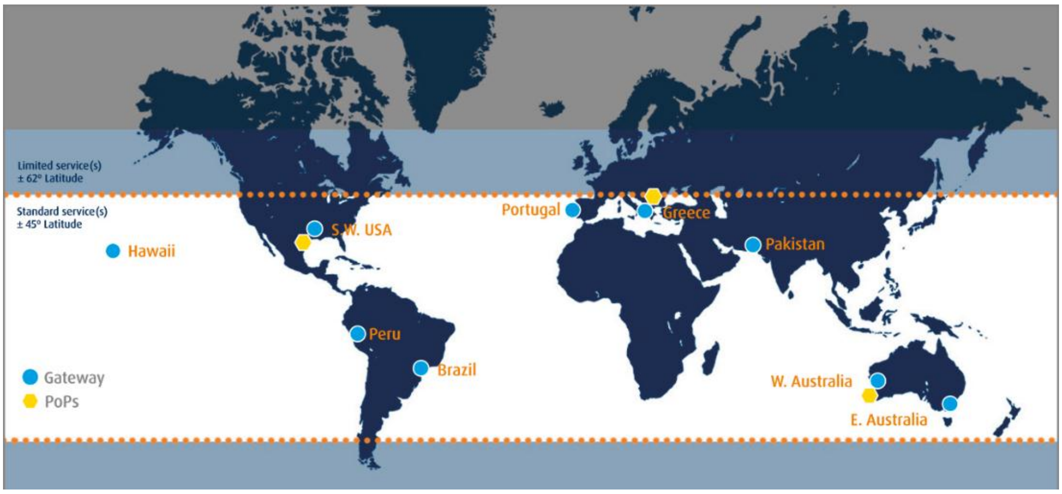



Figure 22: Current O3b coverage

O3b system has deployed as many GES around the world as required (see Figure 22) in order to every satellite always see at least one GES. It means that ISL (Inter-Satellite Links) are not required for this constellation.

O3b satellite's payload consists of a powerful Ka-Band communications system. Each satellite has 12 fully steerable Ka-Band antennas. 2 beams are for gateway connections and 10 beams are for remotes terminals, using 4.3 GHz of spectrum (2x216 MHz per beam). Each antenna provides a data throughput of 1.6 GBit/s (800 MBit/s for up and downlink) resulting in a total capacity of 16 GBit/s per satellite.

O3b main features are summarised in Table 17:

| | |
|---|---|
| ***Altitude*** | **8062 km** above the sea level |
| ***Visibility*** | Good satellite visibility, augmented by the use of satellite diversity techniques. |
| ***Number of satellites*** | Currently **12 satellites** with a lifetime of 10 years.<br>On December 2015 it was published that O3b ordered 8 more satellites to Thales Alenia Space (the manufacturer of current satellites in orbit) |
| ***Ground Period*** | **360 min** (4 contacts per day) |
| ***Coverage*** | Optimal coverage between 45º north/south latitude.<br>It provides 10 beams per region (7 regions), totaling 70 remote beams per 12 satellite constellation.<br>Beam coverage around 700 km diameter. |
| ***Latency*** | O3b declares round trip time (RTT) latencies of around **150 ms**. |
| ***Waveform*** | Forward: DVB-S2 (with ACM)<br>Return: DVB-RCS and DVB-S2 ACM Continuous Carrier |
| ***Capacity*** | O3b provides throughputs and low latency backhaul compatible with all forms of last-mile solutions, including 2G, 3G, 4G, WiMAX and LTE.<br>Each O3b satellite is able to provide up to 16 Gpbs (up to 1.6Gbps per beam (800Mbps x 2)). |

| | |
|---|---|
| ***Routing*** | O3b does not use ISL. Therefore, it requires several GES distributed worldwide. It can be seen at Figure 22 current 9 GES distributed in order to every satellite has always visibility to one of these GES. |

Table 17: O3b MEO/Ka system main features

Figure 23 shows the O3b network architecture adapted for the railway domain. It can be observed how shall be always at least one satellite visible from users points of view. In addition, each satellite has also a visible GES.

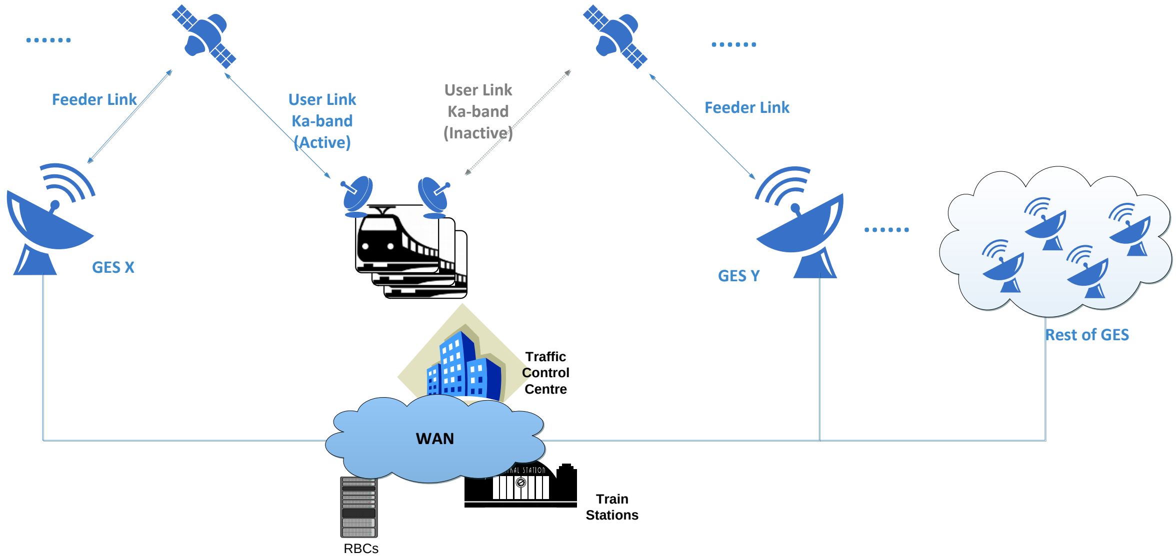



Figure 23: O3b SATCOM architecture

### 6.2.6 Thuraya

Thuraya is a regional satellite communication system that provides voice and data services in Europe, the Middle East, North, Central and East Africa, Asia and Australia (see Figure 24) by means of 2 GEO satellites.

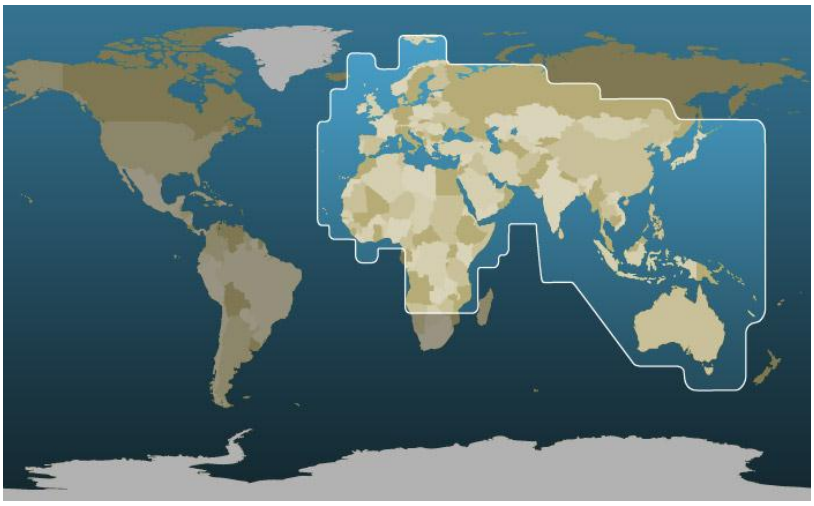


Figure 24: Thuraya satellite coverage

In addition to satellite coverage, Thuraya has an agreement with more than 300 GSM partners worldwide in order to offer GSM roaming services over land-based mobile GSM networks. It is an interesting feature since dual mode terminals (satellite and GSM) are capable to change the access network when the favourite/current one is not available. Figure 25 shows current GSM coverage provided by GSM partners worldwide.

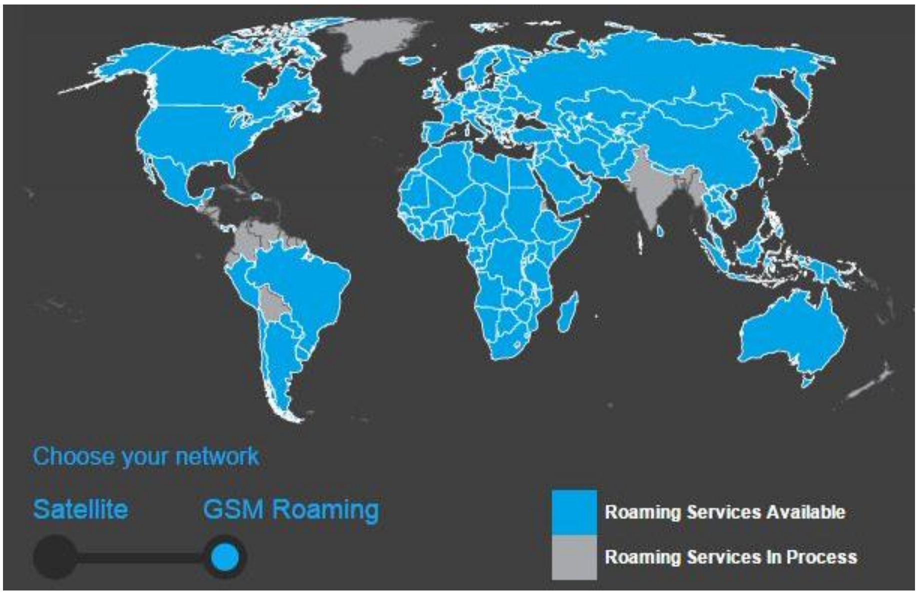



Figure 25: Thuraya GSM coverage provided by partners worldwide

In this sense, this dual coverage is complemented with SIM compatibilities between systems (satellite and terrestrial GSM). It means that Thuraya SIM cards work in regular GSM mobile phones, and vice-versa (as long as the SIM provider has a roaming agreement with Thuraya).

Thuraya's satellites have been designed to achieve network capacity of about 13,750 telephone channels. Thuraya's handheld terminals are comparable to GSM handsets in terms of size and appearance, as well as in voice quality (although it introduces a noticeable delay due to the distance between terminal and GEO satellite).

Regarding Thuraya handhelds, it is interesting to highlight that exist a kind of *sleeve* that adapts to several commercial GSM phones with the aim of converting them (regular GSM phones) to SATCOM terminals (see Figure 26). These terminals are called "Thuraya SatSleeve", and can reduce costs.

Figure 26: Thuraya SatSleeve terminals (enable regular GSM terminals as a Satcom terminals)

Thuraya access scheme is based on TDMA (Time Division Multiple Access), and the service is operated in L-band (it refers to the user link, which makes possible the use of handhelds). Frequencies at user-link are the following:

- *Earth-to-space*: 1626.5-1660.5 MHz
- *Space-to-Earth*: 1525.0-1559.0 MHz

In the feeder-link, Thuraya uses C-band for the uplink and S-band for the downlink:

- *Earth-to-space*: 6425.0-6725.0 MHz
- *Space-to-Earth*: 3400.0-3625.0 MHz

Regarding services, Thuraya provides voice and data communications:

- Voice communications with handhelds or fixed terminals
- Data with satellite handhelds: 60kbps downlink / 15 kbps uplink
- Data with fixed SATCOM terminals: 144 kbps downlink
- SMS
- Some other services related with voice: missed calls, voicemail, call waiting....
- Etc

### 6.2.7 Inmarsat 4 (BGAN) and 6 (ICE) (GEO L-band)

Inmarsat, like Iridium, is a proprietary commercial satellite system that offers global coverage. It has been chosen to be analysed as a current narrowband satellite system for railway safety-critical applications due that:

- Global coverage (achieved with 3 GEO satellites, see Figure 27).

- Lots of manufacturers providing different types of HW solutions.
- L-band user-link. It could imply omnidirectional antenna, reducing this way complexity, maintenance and cost.
- Although it is considered as narrowband system, the Inmarsat BGAN can achieve a throughput of 492kbps. It means that it provides an extra bandwidth that could be used to offer new future safety-critical applications, or even some non-safety critical applications with low bandwidth requirements.
- Available immediately
- Programmed upgrades coming soon (Inmarsat Global Xpress I-5 satellites and ICE Inmarsat 6 satellites).

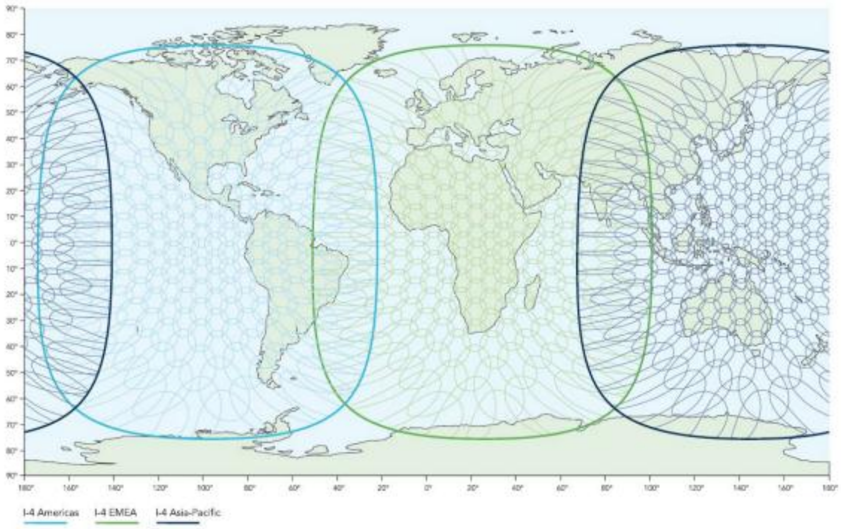



Figure 27: Inmarsat 4 (BGAN) satellites beams

Regarding the air interface, Inmarsat 4 is based on:

- Signal waveform for Forward link – TDM – (to be completed)
- Signal waveform for Return link – MF-TDMA – (to be completed)

Inmarsat 4 lifecycle is not aligned with the replacement of GSM-R starting at 2023. In this sense, it is expected that next generation (*i.e.* Inmarsat 6) of Inmarsat systems can also offer a good solution for providing safety communications to train communications.

Inmarsat announces recently that Airbus Defence and Space (Airbus) was awarded with he contract to build the first two mobile communications satellites for Inmarsat's sixth-generation fleet. The contract is for the construction of the two satellites, where Airbus deliver the first satellite, Inmarsat-6 F1 (I-6 F1), by 2020. Uniquely for Inmarsat, the sixth-generation fleet will feature a dual-payload with each supporting both L-band and Ka-band services. The new satellites will represent a step change in the capabilities and capacity of Inmarsat's L-band services.

This new constellation confirms its continued commitment to delivering advanced L-band services for decades to come and to maximising the growth opportunities that they see in this spectrum. The new satellites will provide significantly greater L-band capacity and will be capable of supporting a new generation of more advanced services. I-6 satellites are designed to remain in service for a minimum of 15 years.

The ICE (Inmarsat Communications Evolution) PPP (ESA and UK Space agency contract) will offer industry an opportunity to propose innovative technologies and solutions that could enhance and expand the capabilities of mobile satellite communications, including associated products and services. Inmarsat (as prime contractor) will undertake a feasibility study focused on identifying enabling technologies, both in space and on the ground, that could maximise the throughput and coverage of satellite communications; create lower cost, smaller terminals; develop modular components that can be easily integrated into a broad range of devices; and maximise the commercial opportunities presented through the development of connected applications – from automated transport to environmental monitoring.

These new satellites are aiming at providing two main types of communication links: on one hand, an evolution of the BGAN (I4) which is offering real-time service at higher data rates and on the other hand, a new waveform for supporting the low data rates required for M2M related services by using very small and low-cost terminals.

#### 6.2.8 GEO S-band (Eutelsat W2A)

In May 2009, Inmarsat and Solaris Mobile (a joint venture between Eutelsat and Astra) were awarded each a 2×15 MHz portion of the S band by the European Commission. The two companies were allowed two years to start providing pan-European MSS services for 18 years. Allocated frequencies were 1.98 to 2.01 GHz for Earth to space communications, and from 2.17 to 2.2 GHz for space to Earth communications. Eutelsat W2A satellite launched in April, 2009 and located at 10° East is currently the unique satellite in Europe operating on S band frequencies. Since it seems that such initiative was not successfully progressed and taking into account that this band was proposed to support mobile broadcast and interactive return channel, as it can be seen at [RD-04], it is considered by similarity analysis against the requirements for the railway safety applications that it can be an opportunity for both in order to, on one hand exploit the S-band satellite and on the other hand, to provide a regulated band to allocate the railway safety services. It is important to point out that L-band was discarded since it is already most saturated (*e.g.* allocating aeronautical services in AMS(R)S), whilst 2GHz S-band was assigned to try to exploit the satellite mobile broadcast TV and interactive return channel, through to DENISE [RD-04] and also SAFETRIP [RD-05] projects, but currently it seems not to evolve.

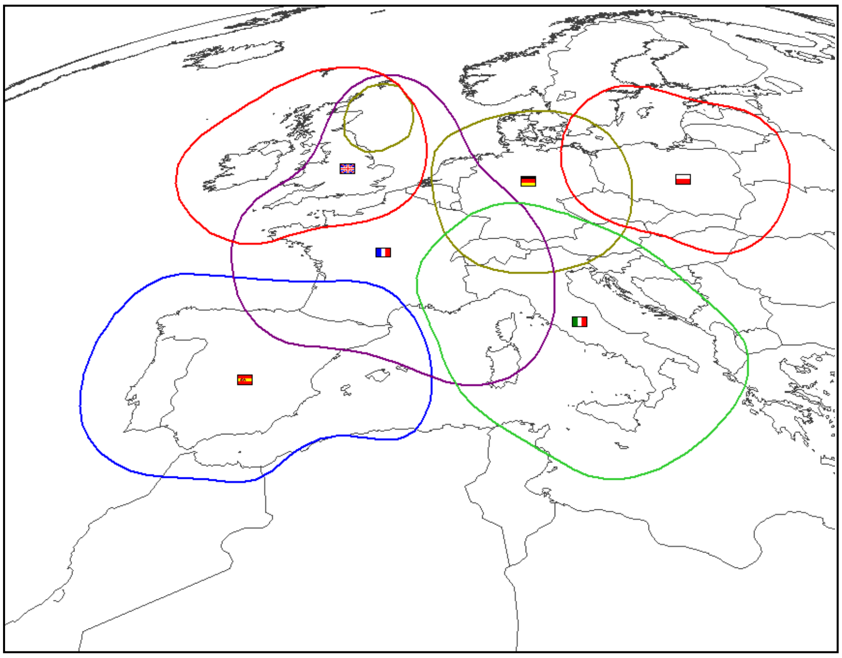


Figure 28: Eutelsat 10A user link coverage

Figure 28 shows Eutelsat 10A user link coverage.

### 6.2.9 GEO C-band (5GHz)

Traditionally, C-band has been used for providing broadband satellite services, and although its use (mainly in Europe) has decrease lately by the reallocation to Ku-band and more recently to Ka-band, satellite operators still rely on this frequency band. Proof of this is the deployment that (for example) Intelsat is performing with its EpicNG (Next Generation) constellation, a group of 7 high performance next generation satellites (HTS, High Throughput Satellites) that are going to be launched during next years (from 2016 to 2020). The Intelsat EpicNG platform will use C-, Ku- and Ka-bands, combining wide beams with spot beams, and taking advantage of technologies such as the frequency reuse[10] (*i.e.* the use of the same frequency multiple times simultaneously).

One of the EpicNG satellites providing coverage to Europe, the IS-33e, was launched on August 2016, and it will provide services in C- and Ku-band, as it can be seen at Figure 29.

[10] Intelsat applies multi-spot beam technology to C- and Ku-band, in addition to Ka-band (despite the false extended impression that spot-beam frequency reuse is only available for Ka-band).

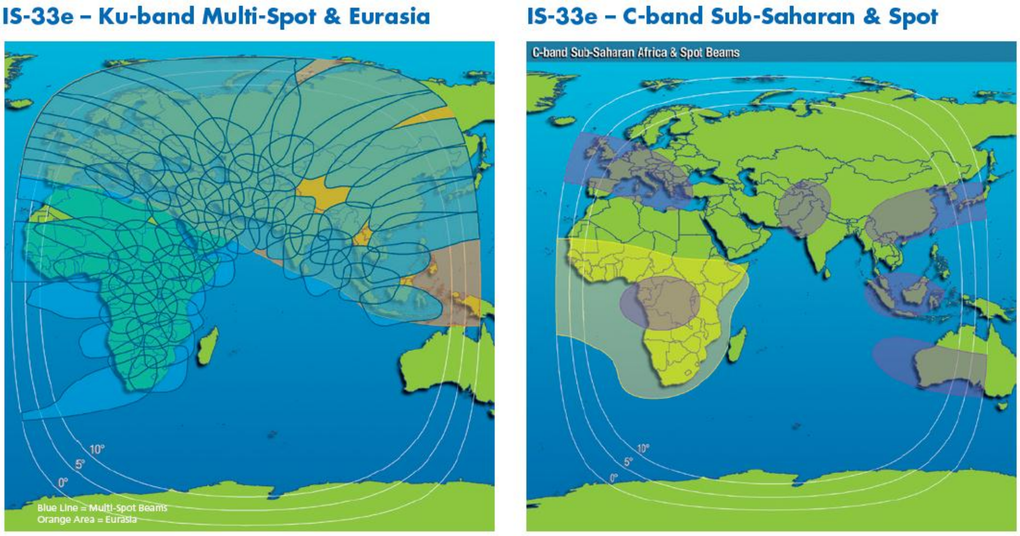



Figure 29: IS-33e EpicNG satellite coverage

The IS-33e is the second EpicNG next-generation high-throughput satellite launched by Intelsat. The satellite design allows a combination of spot beams and wide beams, being able this way to meet all bandwidth demands (from narrowband to broadband).

The Intelsat EpicNG constellation will mainly support to following services:

- Government and military communications
- Maritime and aeronautical data services providers
- Telecommunications for oil and gas industry
- Telecommunications operators
- Television distribution and broadcast service providers
- Etc.

Although there is a strong pressure from terrestrial mobile communication industry to transfer lower part of C-band, currently for SATCOM use, to terrestrial ones, there are also some other initiatives for the use of C-band for SATCOM. In this sense, and in the frame of the integration of the RPAS into the non-segregated airspace, it is currently proposed the 5GHz band (5030-5091 MHz) to provide C2 services via RLOS and BRLOS (*i.e.* SATCOM). Regarding RLOS, in the last WRC was approved 5GHz for C2 RLOS services but it is still pending for SATCOM services. At this moment, there exist several European initiatives (*e.g.* from ESA, EUROCAE, etc) in order to find out the most suitable bearer able to allow sharing this band for both, RLOS and SATCOM. It is known that there exists some proposal for this type of bearer; however, this information is not public.

#### 6.2.10 GEO X/Ka band (GOVSAT1)

X-band and Ka-band frequencies were historically reserved for military SATCOM services. However, it is worth to remark that EDA (European Defence Agency) Ministers of Defence in November 2013 endorsed the roadmap on Governmental Satellite Communications to develop a future dual civil-military capability by 2025 via a user-driven programmatic approach. The main argument comes from the satellite communications have become critical elements for defence, security, humanitarian, emergency response or diplomatic communications and they are a key enabler for civil and military missions/operations in particular in remote and austere environments with little or no infrastructure. Additionally, there is strong potential for a dual-use cooperative approach. The objective of EDA's proposal for Governmental Satellite Communications (GOVSATCOM) is to prepare the next generation **in the 2025 timeframe**. In close cooperation with Member States, the European Commission and the European Space Agency, the programme includes:

i. Establishing a GOVSATCOM Operators User Group of the five Member States (DE, ES, FR, IT, UK) that operate systems;
ii. Identifying and producing Common Staff Targets for future mission requirements;
iii. On this basis, undertake a gap analysis and an updated Strategic Research Agenda;
iv. Coordinating civil and military requirements; and
v. Preparing a Category B project for Member States interested in due course.

It is important to highlight that it has been considered the SATCOM as the backbone of many infrastructures where some are strictly security related. In this sense, security requirements are taken into account when providing SATCOM, particularly in the areas of **transport** and space where the supported information systems are vital for the safety of users.

From [RD-06], it is mentioned the **rail traffic management** as one of them. Although the new European train control system is essentially based on ground-based radio communications between the trains and the Control Centres. It is well known that several initiatives form ESA and also EUAR (EC) has been launched to investigate about the feasibility of satellite based solutions (SATCOM and SATNAV) since it can increase capacity and make train traveling economically more attractive. Future needs could be significant, as 30% of current road freight over a 300 km range are forecast to move to other transport modes such as rail or waterborne transport by 2030, and more than 50% by 2050. Currently, the Shift to Rail (S2R) consortium (EC initiative) is conducting several studies to increase the attractiveness and efficiency of rail transport, and IP2 workpackage is including activities related to the promotion of SATCOM technology for safety railway communications.

One of the more recent proposals comes from Luxemburg and it is named: **GovSat**. It is a brand operated by LuxGovSat S.A., a public-private joint venture between the Luxembourg Government and SES, the world-leading satellite operator.

The main mission of this satellite Ka/X-band dual solution is to provide secure, reliable and accessible satellite communication services for governments – addressing the demand for connectivity resulting from defence and institutional security applications.

It is introducing a new type of geostationary satellite aimed exclusively at government and defence users. GovSat-1 is a multi-mission satellite that offers X-band and Military Ka-band capacity. It is a highly secure satellite with encrypted command and control and anti-jamming capabilities. The company's first satellite GovSat-1 is scheduled to be operational in Q4 2017.

LuxGovSat will lease satellite capacity on a non-preemptable basis, and their users have full control over the management of their services. Capacity leases will be offered to governments and institutions on a full or actional transponder basis (MHz). In addition, the 24/7 secure operations will be staffed by operators and experts with the security clearance needed to support their users.

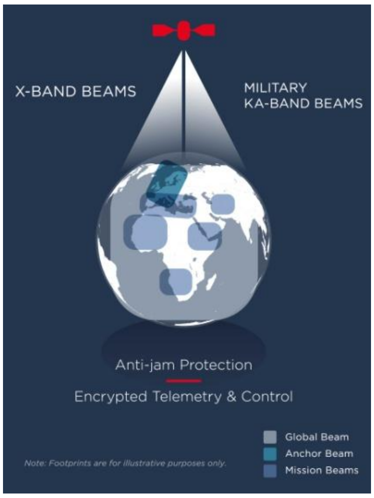



Figure 30: LuxGovSat system coverage

This SATCOM system is aimed at providing capacity for the following applications:

**Capacity for Institutional applications:**

- Civil-military inter-agency collaboration
- Strategic and tactical networks
- Emergency response
- Disaster recovery
- Protection of natural resources
- Remote government offices

**Capacity for defence applications:**

- Remote army operations (Mission to HQ communications)
- Communications on the move (COTM)
- Communications on the pause (COTP)
- Maritime operations
- Aero operations (ISR) Defence Applications

The satellite GovSat1 is characterised for the following security features:

- Encrypted telemetry and control
- Anti-Jamming
- Security accredited facilities
- Frequencies reserved to government and defense use
- Security cleared experts and operations.

About X and Ka bands, they are characterised by:

- **X-Band**: frequency band reserved for governments and institutions, ideal for establishing secure and robust satellite communication links.
    - Global beam

- Extensive coverage from 50°W to 90°E and 70°N to 70°S
- Ideally positioned to address communications within NATO's stated Level of Ambition of a Major Joint Operation
- Enables maritime operations over the Atlantic and Indian Oceans

   - Multiple-mission beams
      - High-power coverage over key mission areas
      - Ideal for establishing critical and secure communications in theatres of operations
      - Fully flexible and steerable
- **Ka-band**: frequency band reserved for governments and institutions, ideal for establishing secure communications for high- throughput or mobility applications.
   - Anchor beam
      - Ideal for connecting European headquarters to any of the GovSat-1 mission beams
      - Ideal for interconnecting headquarters or other key institutional or defence sites within Europe
   - Multiple-Mission beams
      - High-power beams to enable high-bandwidth applications over small antennas
      - Ideal for Intelligence, Surveillance and Reconnaissance (ISR) and Communications on the Move (COTM) applications.
      - Providing high-power coverage over the Mediterranean Sea

### 6.2.11 Smart LNB (Eutelsat)

#### 6.2.11.1 System Overview

The SmartLNB is a solution recently deployed by Eutelsat that consists of providing a low throughput **return channel** (in Ku/Ka-band) to existing broadcast services and M2M applications. This new technology is based on a next-generation electronic feed (with an embedded DVB demodulator and an IP transmitter) that enables a variety of low throughput applications via (GEO) satellite. Therefore, this technology adds low throughput return channels to existing forward channels.

This new technology has been though initially for 2 main markets:

- ***Interactive TV services***, giving end users easy access to connected TV services such as:
   - Pay-per-view
   - Social TV
   - Personal subscription management
   - etc.
- ***M2M*** (Machine-to-Machine), where applications with small volumes of data are collected or exchanged, such as:
   - e-Health
   - Smart-grids
   - Remote diagnostics and telemetry
   - Data gathering
   - SCADA (Supervisory Control And Data Acquisition)

- Enviromental monitoring
- FW/SW updates
- etc

The main features of SmartLNB are summarised below:

- Low cost equipment providing return satellite link up to 160 kbps per terminal
- Use of multiple frequency bands Ku and Ka
- Highly efficient transmission protocol suitable for millions of connected objects.

#### 6.2.11.2 System architecture

The SmartLNB solution relies on forward existing technologies in Ku or Ka bands, since the main improvement is the introduction of a new LNB (Low-Noise Block) technology capable of providing a new low throughput return channel (in Ku or Ka bands, as well). SmartLNB is optimised for bursts and message-type traffic on the return link. The transmission protocol provides modulation and asynchronous access scheme with very high spectrum efficiency (by using Enhanced Spread Spectrum Aloha access scheme). In addition, it is worth to point out that forward link channel is based on DVB-S2 standard. Both radio channels (forward and return) implemented in the smartLNB terminal are referred as F-SIM (Fixed Satellite Interactive Multimedia services) protocol. This protocol has been adopted by the recently deployed Eutelsat Broadcast Interactive System (EBIS) and F-SIM can be seen as an evolution of legacy ETSI S-MIM standard [RD-07].

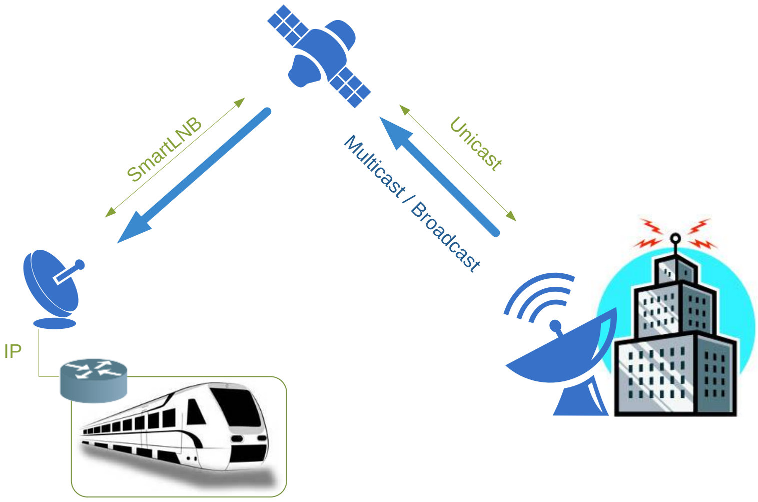



Figure 31: SmartLNB solution system architecture

### 6.2.12 GEO Ku-band

#### 6.2.12.1 System Overview

Ku band is the portion of the electromagnetic spectrum comprised between 12 and 18 GHz, and is primarily used for satellite communications.

GEO Ku-band satellite communication systems are nowadays common systems to provide broadband data communications to fixed and on-the-move terminals. It is currently a mature technology that provides service to several markets with high success. That's why Ku-band is currently widely used and it is expected to be a reliable SATCOM solution for the future with new satellites adding improvements and new features.

Satcom solutions currently deployed to provide non-safety critical services on railways (such as internet for passengers) are deployed over GEO satellites in Ku-band. For example, 21Net (a company delivering connectivity solutions for trains based mainly on SATCOM), has based its solutions deployed over different HSL (*High Speed Lines*) worldwide on GEO Ku-band solutions. They have taken advantage of the most convenient satellite in each case (such as for example the HISPASAT for the Thalys HSL) and the whole SATCOM system including HUB and remote terminals (initially EMC proprietary solution and subsequently changed to iDirect proprietary solution).

As another example, INDRA is currently participating within the design and deployment of a Satcom solution for High Speed trains to provide Internet for passenger in Spain (AVE trains). And this solution also considers the use of a GEO satellite and the Ku-band (such as the HISPASAT 1D or 1E provide). The system will be based on iDirect proprietary solution.

#### 6.2.12.2 System architecture

GEO/Ku-band solutions have, in general, the system architecture depicted in Figure 32, where the user link relies on Ku-band. The feeder link could be Ku-band, as well, or different (Ka, for example), since this link does not represent the limitation part.

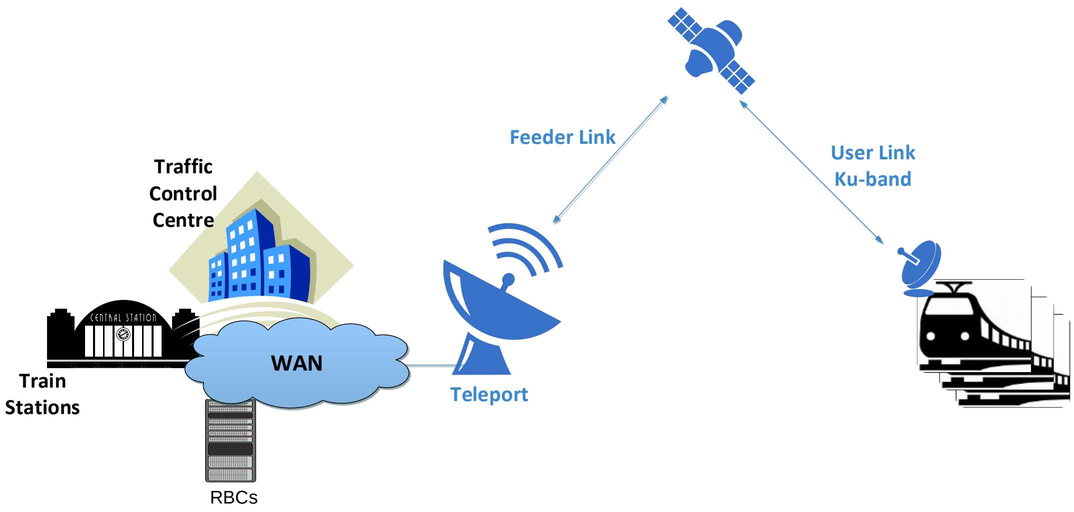



Figure 32: GEO/Ku-band SATCOM architecture

Regarding the communication solution (basically ground and user segments), it depends on the equipments selected in each case. Considering as an example the **iDirect solution** (non-standard but widely used), it is based on a DAMA system (see section §6.3 for more information about access schemes) where the access scheme is proprietary and derived from a Time Division Multiple Access (TDMA) scheme, named Adaptive-TDMA (ATDMA). The ATDMA allows the efficient use of bandwidth since it is able to optimally changing the return channel configuration to match the conditions of the over-the-air links and the constraints of the terminals (*i.e.* it applies a kind of ACM mechanism). The idea behind this ATDMA scheme is to use different inbound or inroute carriers (or groups) (*i.e.* from terminals to HUB) with different performances in order to be able to use them according to terminal's link conditions.

The management of the system is located at the HUB, which is constantly analysing remote terminals demand and assigning bandwidth according to their QoS (Quality of Service) and CIR (Committed Information Rate) limitations and their current link conditions. This assignment process includes also the selection of optimal in-route compositions based on aggregate signal conditions and capacity requests of all remotes.

The **iDirect** forward link supports both DVB-S2 and DVB-S2X standards with ACM (Adaptive Coding and Modulation), providing this way a high bandwidth efficient transmission for any type of service such as voice, data and video applications, business continuity networks, cellular backhauling or military/government communications.

These type of system solutions can provide high availability/reliability by integrating redundancy into critical components with auto-switchover mechanisms.

### 6.2.13 <u>Inmarsat 5 - Global Xpress (GX)</u>

#### 6.2.13.1 System Overview

With the launch of Inmarsat-5 F3, Inmarsat completed in mid-2015 the first phase of its new satellite constellation consisting of 3 GEO satellites, named Global Xpress (GX).

Global Xpress is the last Inmarsat satellite solution that offers the first global superfast broadband system. It offers the unique combination of seamless global coverage from a single operator and consistent higher performance up to 50Mbps. The capacity of this new constellation is, according to the company, two orders of magnitude greater than its predecessor (Inmarsat-4 BGAN). It is also the first Ka-band global constellation providing mobile services, with the ability to offer high-speed broadband on land, sea and air.

Therefore, based on Ka-band technology, Global Xpress delivers very high speeds through compact terminals, using spectrum that is far less congested.

Terminals are available in mobile, portable and fixed formats for customers on land, at sea and in the air, supporting connectivity for other user terminals such as smartphones, tablets and laptops.

For extra resilience, Global Xpress is complemented by standard broadband services on the Inmarsat-4 (BGAN system), which deliver currently 99.9% network availability (according to Inmarsat information). This way, GX is a global Ka band SATCOM system with a fully integrated L-band backup.

#### 6.2.13.2 GX architecture

Global Xpress is a global satellite constellation that offers mobile communications through 3 GEO satellites. Each one of these satellites provides coverage by means of 89 fixed spot beams (Global Payload) and 6 steerable high capacity spot beams (High Capacity Payload).

Each satellite is controlled by means of 2 different Satellite Access Stations (SAS), which provide backup with automatic switchover. These SAS are separated hundred of kilometers in order to also offer site diversity.

The ground segment provides SASs and also a multiprotocol label switching (MPLS) infrastructure that interconnects all Inmarsat L-band and Ka-band resources. The ground segment also provides secure enclaves for supporting Customer-specific equipment and services.

Both user link and feeder link uses Ka-band, which allows high bandwidth but limited types of terminals, since the use of directive antennas is required (handhelds are not allowed).

Figure 33 shows GX architecture taking into account only one of the three satellites.

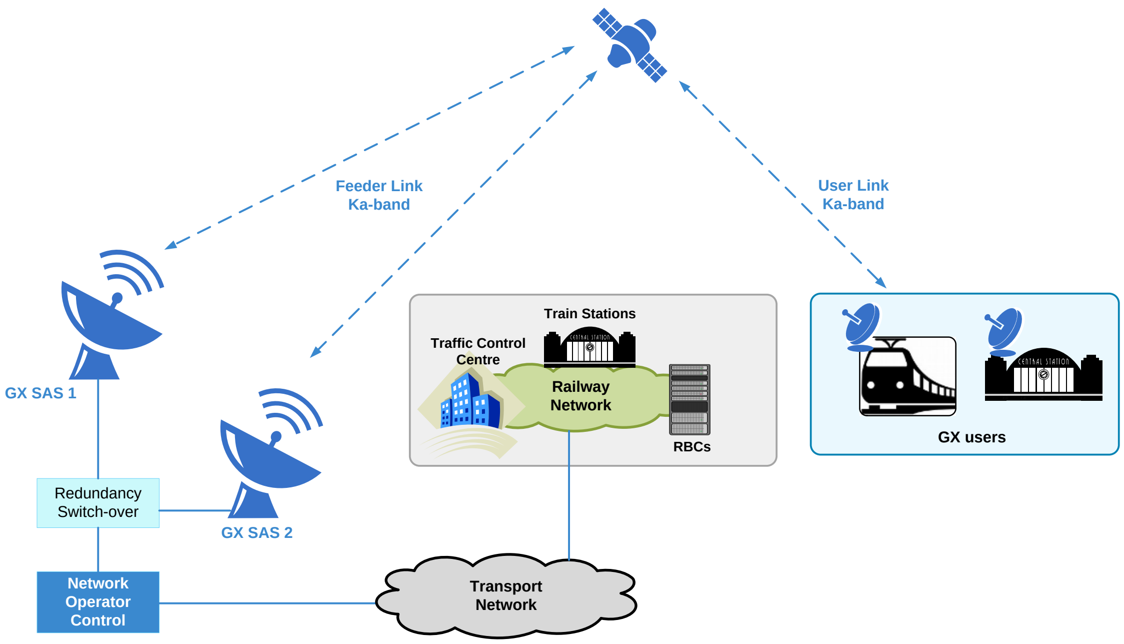



Figure 33: Global Xpress architecture for railways

Following subsections describes with more details the three segments of this architecture.

#### 6.2.13.2.1 Space segment

GX space segment is composed (at this moment) of 3 Inmarsat-5 GEO Ka-band satellites, which provide high-speed mobile broadband communications with global coverage by means of 89 fixed spot beams and 6 steerable high capacity spot beams (each satellite).

Figure 34:Inmarsat 5 satellite (Boeing 702HP)

With an expected lifetime of 15 years, the first three Inmarsat-5 satellites were launched between 2013 and 2015:

- *Inmarsat-5 F1* – launched on 6 December 2013 to deliver regional GX services for Europe, the Middle East, Africa and Asia
- *Inmarsat-5 F2* – launched on 1 February 2015 to deliver regional GX services for the Americas and the Atlantic Ocean Region
- *Inmarsat-5 F3* – launched on 28 August 2015 to deliver regional GX services for the Pacific Ocean Region.

Although the constellation is fully operative worldwide, there is also a 4$^{th}$ satellite underway that is expected to be launched during 2017 to provide additional GX capacity.

Figure 35 shows coverage provided by each Inmarsat-5 satellites currently launched (*i.e.* F1, F2 and F3). It can be observed that some areas of Polar Regions are not covered by GX.

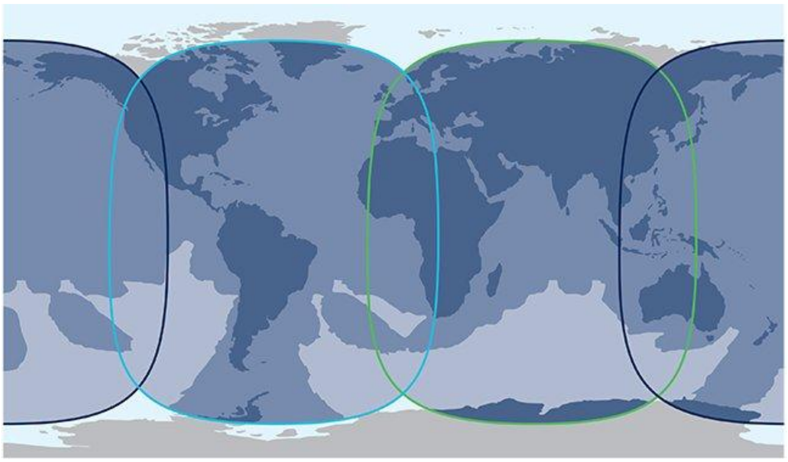


Figure 35: Inmarsat-5 satellites coverage

6.2.13.2.2 Ground segment

Each Global Xpress satellite is operated by two redundant earth stations (also known as SAS, *Satellite Access Stations*) to ensure higher network availability. Therefore, the ground segment is composed of 6 SAS supporting global coverage and site diversity.

The 2 GW SAS sites in each ocean region (*i.e.* of each satellite) are used as a backup and with automatic switchover. Furthermore, they are separated hundreds of kilometres with the aim of avoiding SAS outages and improving system availability.

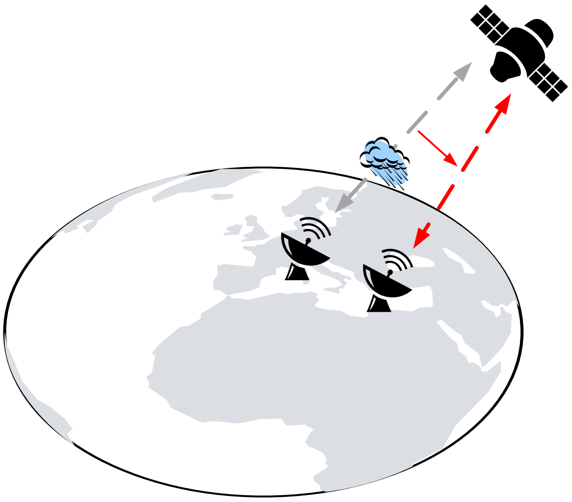


Figure 36: Global Xpress SAS automatic switchover

6.2.13.2.3 User segment

Since Global Xpress works only in Ka-band, directive antennas are required to close the link budget between terminals and satellites. Therefore, GX partners have develop fixed, transportable, 'flayway' and' manpack' terminals with directive antennas from 30 cm to more than 1m (depending on each market and its requirements).

Hence, handhelds are not supported by GX. Previous Inmarsat-4 system (BGAN) allowed the use of handhelds. It is so because this previous GEO constellation uses the L-band for the user link, a lower frequency band not affected by weather conditions and capable of closing the link budget with satellite using an omnidirectional antenna and a reasonable power transmission.

GX terminals take advantage of the use of adaptive coding and modulation (ACM) to maintain link in adverse situations like with rain-fade.

Regarding user data rates, a terminal with a 60 cm antenna (as an example), can achieve maximum data rates of 5 Mb/s uplink and 50 Mb/s downlink.

6.2.13.2.4 Services

GX market is mainly oriented to sectors of aviation, marine, business and government.

#### 6.2.13.3 Air interfaces

On the forward link, Global Xpress is based on the standard DVB-S2 with ACM (Adaptive Coding Modulation). ACM is a very interesting technology since it allows the system to change the coding (FER, Forward Error Correction) and the modulation of a link to compensate for changes in link conditions. Usually these changes are due to weather conditions (such as rain fade), but it can also come from other sources, such as interference or even RF level changes. With ACM techniques, satellite networks can maximize link throughput by dynamically adjusting the link to a more or less robust MODCOD (modulation and coding) according to weather conditions (rain, clear sky...).

By the use of ACM, Global Xpress allows the change of MODCODs in real time and per terminal depending on current reported signal to noise ratio.

On the return link, Global Xpress uses MF/TDMA. The return channel is divided into multiple carriers with several configurations including more and less robust modulations and coding. This way, satellite terminals are assigned to the slots (TDMA) of the different carriers depending on:

- Terminal features (antenna size, power)
- Channel (fadings, clear sky...)
- QoS parameters
- etc

### 6.2.14 GEO Ka-band

Ka band is the portion of the electromagnetic spectrum comprised between 26.5 and 40 GHz, and is used for satellite communications. It is worth mentioning that Ka band has a portion reserved for military and governmental services and other one for civil services.

GEO Ka-band satellite communication systems are growing quickly due to its high bandwidth available and its application to broadband services. The use of this band is more recent than the Ku-band since Ka-band is more susceptible to rain fade than Ku-band (in general, the higher the frequency, the more a signal is susceptible to rain fade). This way, when new applications requiring more bandwidth have appear and Ku-band has been almost-overload, investment on Ka-band technology has raised.

Nowadays Ka band technology is growing quickly and gaining maturity, which can be shown considering the high number of satellites/constellations providing services in Ka-band:

| | |
|---|---|
| *GEO* | Eutelsat Ka-Sat, W3C... |
| | Inmarsat 5 (Global Xpress) |
| | Avanti Hylas 2, 2B... |
| | Measat 5 |
| | Arabsat 5B, 5C... |
| | Telenor Thor7 |

| | |
|---|---|
| | *Etc.* |
| ***MEO*** | O3b |
| ***LEO*** | Iridium Next (ongoing) |

Table 18: Ka-band satellites/constellations

#### 6.2.14.1 System architecture

The GEO/Ka-band SATCOM system architecture is the same that the GEO/Ku-band architecture, where the only difference is in the frequency band used. Figure 37 shows a general GEO/Ka-band SATCOM system architecture, where the user link uses the Ka-band. The feeder link could also use the Ka-band or a different one, since this link does not represent the limitation part.

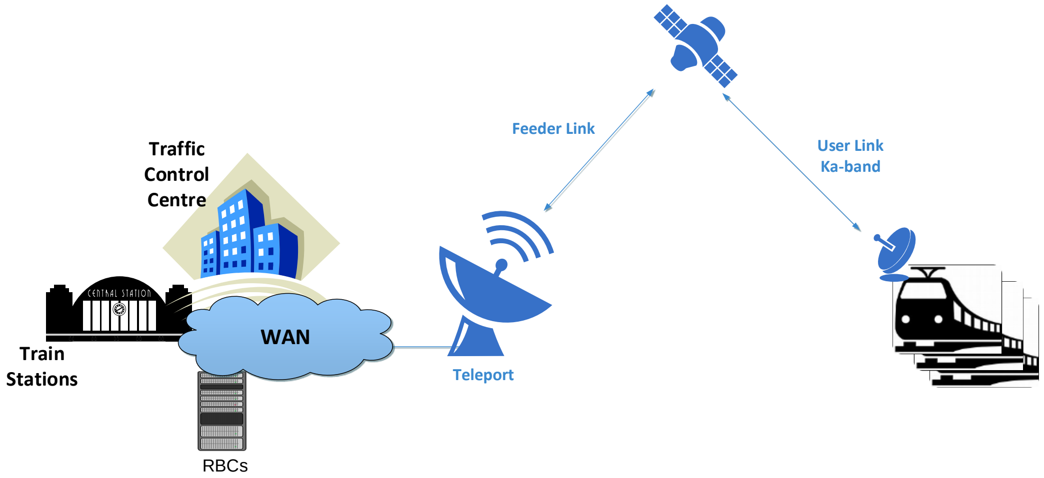



Figure 37: GEO/Ka-band SATCOM architecture

The communication solution (ground and user segments) in this case is the same that in Ku-band (except for the RF and antenna equipments). It means that at designing phase it can be analysed which SATCOM solution (standard or proprietary) is more convenient for a specific solution.

#### 6.2.14.2 High Throughput Satellites (HTS)

One interesting feature of Ka-band (although the band a priori it is not a constraint) is currently the increase of a type of satellites capable to provide many times the throughput of a traditional FSS satellite for the same amount of allocated frequency on orbit. These satellites are named *High Throughput Satellites* (HTS), and are able to increase throughput radically (and reducing this way the cost per bit delivered) by means of defining **multiple spot** beams and **frequency reuse** techniques. And although HTS are not only specific of Ka-band, the fact is that the amount of bandwidth available (and of course the characteristics of the band) make this band a good candidate to be used on HTS.

A HTS is defined as a satellite that uses a large number of small spot beams distributed over a particular service area. These spot beams provide high signal strength and signal gain (EIRP and

G/T), which allow the satellite to close links to small aperture earth stations at high data rates with positive rain-fade margin to provide good overall link availability.

Main features of HTS solutions are:

- Area to be covered is divided into many small spot-beams (unlike conventional satellites where one single beam covers the whole area)
- Small spot beams support higher performance than one conventional beam
- In addition, spot beams allows frequency reuse increasing efficiency and enabling high data rates.

HTS satellites can include both Ka-band and/or Ku-band platforms, each one with its own strengths and weaknesses that make them better suited for some or other applications.

In general (but more significant for Ka-band), it is very important the trade off between coverage and performance, since small spot beams can provide better performance than broader beams, but also cover a small area.

Examples of current HTS are:

| | | |
|---|---|---|
| **Eutelsat Ka-SAT**<br>• *Launch Date*: Dec 2010<br>• *Freq. Band*: 82 Ka spot-beams<br>• *Coverage:* Europe and Mediterranean Basin | **ViaSat-1**<br>• *Launch Date:* Oct 2011<br>• *Freq. Band*: 56 Ka transponders<br>• *Coverage:* North America | **EchoStar 17**<br>• *Launch Date:* Jul 2012<br>• *Freq. Band*: 60 Ka<br>• *Coverage:* North America |
| **HYLAS 2**<br>• *Launch Date:* Aug 2012<br>• *Freq. Band*: 30 Ka spot-beams<br>• *Coverage:* Northern and Southern Africa, Eastern Europe and the Middle East | **Astra 2E**<br>• *Launch Date*: Sept 2013<br>• *Freq. Band*: 60 Ku, 4 Ka transponders<br>• *Coverage:* Europe & Africa | **O3b**<br>• *Launch Date:* 2014<br>• *Freq. Band*: 12 Ka beams each satellite<br>• *Coverage:* worldwide |
| **Inmarsat 5 (GX)**<br>• *Launch Date:* 2013-2015<br>• *Freq. Band*: 89 Ka beams each satellite<br>• *Coverage:* worldwide with 3 satellites | **Telstar 12 Vantage**<br>• *Launch Date:* Nov 2015<br>• *Freq. Band*: 52 Ku transp<br>• South Atlantic, Caribbean, Mediterranean and North Sea | **Sky-Muster**<br>• *Launch Date:* Sept 2015<br>• 110 Ka spot-beams<br>• *Coverage:* Australia |

Table 19: HTS examples

It is paid special attention to the **Eutelsat Ka-SAT satellite**, since it was the first HTS in Europe with 82 Ka-band spot beams connected to a network of 10 ground stations. This configuration allows a frequency reuse of 20 times and offers a total throughput of more than 90 Gbps.

Table 20 shows main features about the Ka-SAT satellite.

| | |
|---|---|
| ***Number of spot beams*** | 82 |
| ***Number of GES (Europe)*** | 10 |
| ***Total capacity*** | Over 90 Gb/s |
| ***Number of countries covered*** | 55 (Europe and Mediterranean Basin) |

| | |
|---|---|
| ***Satellite launch*** | December 2010 |
| ***Lifetime*** | 16 years |

Table 20: Ka-SAT main features

Ka-SAT coverage is showed within Figure 38.

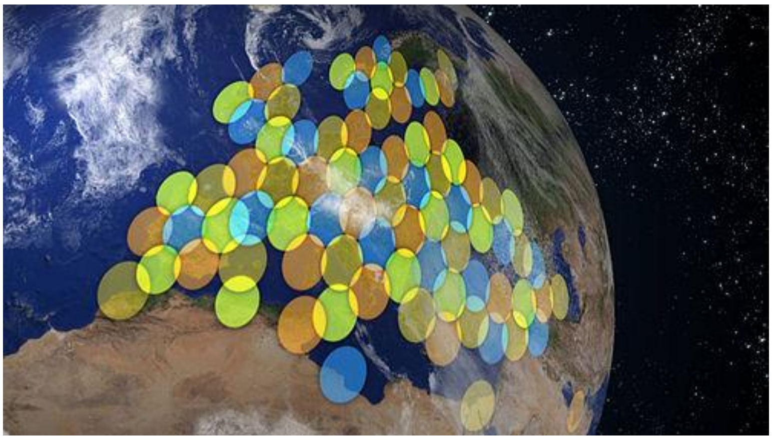


Figure 38: Ka-SAT coverage over Europe (frequency reuse is showed by different colours)

## 6.3 SATCOM ACCESS SCHEMES

The transmission scheme is an essential part of the system to assure critical railway applications requirements. Its selection has a direct impact in the equipment required since the carrier characteristics have influence on the link budget calculations, which determine requirements on satellite terminals.

There are several waveforms and access schemes to be considered which selection depends directly on the final application. Regarding the access schemes they can be classified as:

| | |
|---|---|
| ***Multiple Access*** | DAMA (Demand Assigned Multiple Access)<br>*Ex.: TDMA, FDMA, CDMA, OFDMA...* |
| | RA (Random Access)<br>*Ex.: ALOHA, Slotted-ALOHA, E-SSA, CRDSA, ACRDA...* |
| | Hybrid solutions DAMA + RA |
| ***NO Multiple Access*** | PAMA (Permanently Assigned Multiple Access)<br>*Ex.: TDM, FDM, CDM...* |

Table 21: Satellite communications access schemes

Where,

| | |
|---|---|
| ***DAMA*** | Access scheme consisting of assigning resources to users only when required. Therefore, it is usually used when the system has a lot of users and not resources for all of them. It is a good option when it is not needed a traffic channel permanently established, reducing this way unnecessary resources and rises efficiency. |
| ***Random Access (RA)*** | It is a technology used to send users data bursts randomly, without channel establishing. It is a good option when users mainly send data bursts "randomly" and a few packets exchange are required to complete a transaction.<br>When using RA delay is reduced since not channel establishment needs to be executed each time a data packet has to be sent. |
| ***DAMA + RA*** | DAMA + RA is a good hybrid solution when both types of applications (random data bursts and medium-to-large amount of data) co-exist. This way, RA is available for sending short data messages and DAMA to establish a traffic channel when more data has to be sent. |
| ***PAMA*** | PAMA consists of assigning resources to users permanently. When using a continuous traffic channel for each user that offers also non-safety applications to a large number of passengers, the spectral efficiency achieved using DAMA or PAMA is very similar (refer to [RD-08]). This way, and considering that PAMA ease the operation, (*i.e.* less complex and easy to deploy), and improve delays, a continuous carrier mode has also been considered<br>Therefore, PAMA seems to be convenient for systems providing also non-critical railway applications such as entertainment for passengers. |

Table 22: Access schemes definitions

| | **DAMA** | **RA** | **PAMA** |
|---|---|---|---|
| ***Resource assignment*** | Done by user's request | Not needed | Initially planned |
| ***Assignment duration*** | Up to call/connection duration | Connectivity exists during burst/packet | Assignment can be static for long or semi-static since complete operation/mission. |
| ***Strengths*** | - Efficiency<br>- Flexibility | - Speed (no resource request required) | - Simple solution |
| ***Weaknesses*** | - Complexity (whole operation is carried out by the control station) | - Low control over users<br>- Collisions (retransmissions) may occur | - Not flexible<br>- Inefficient (resources wasted by users are not used by other users). |

Table 23: Comparison among access techniques

## 6.4 SATELLITE COMMUNICATION PROTOCOLS (STANDARDS AND PROPRIETARY)

This section describes different satellite communication standards in order to check their features and if some of them have been thought or adapted for its use on railway applications, *i.e.* considering main impairments due to the 'railway channel', such as catenaries, power arches, tunnels, multipath, etc.

Although communication standards (CS) are mostly describing the OSI layers (defined by ISO) of a communication protocol, within the scope of this project it is only considered L1 (physical layer) and L2 (Link (LLC/ MAC) layer), since both characterize the "bearer".

CS is mainly detailing the transmission scheme. Regarding receivers, each manufacturer is responsible for its implementation. However, sometimes there exist guidelines for the receiver implementation in order to indicate the highest reachable performances.

It is worth mentioning that the use of a standard communication protocol is an interesting solution, since standardization of the bearer enables interoperability, ease the availability of COTS and reduce deployment costs.

Despite CS are conceived to provide particular services taking into account a dedicated satellite constellation and frequency band, they are analysed hereafter as SATCOM technologies separately from the final SATCOM orbit and frequency band, since there are some of them supporting several bands and some of them supporting GEO and non-GEO orbits, as well.

### 6.4.1 DVB-S / S2 / S2X

DVB-S/S2 and their extensions are the most known satellite standards originally created for the transmission of DVB signals via satellite.

The former DVB standard for satellite, DVB-S, was originally created to provide Direct-To-Home (DTH) services for consumer Integrated Receiver Decoders (IRD), as well as cable TV head-end stations and collective antenna systems.

But this first standard and SATCOM technology evolved a lot since the publication of former DVB-S and a second generation of the DVB standard for satellites was created. Therefore, a second generation of the first standard, or DVB-S2, is the standard designed to improve the former DVB-S adding some new features, like LDPC codes, Variable and Adaptive Coding and Modulation (VCM and ACM) and some enhanced modulations (up to 32 APSK). This standard is widely used, even in the railway field (although with non-safety applications), within projects/services like Mowgly or 21Net.


Figure 39: Evolution of DVB standards for satellite

More recently, a new extension to DVB-S2 (also kown as DVB-S2X) provides additional features and technologies for several services, such as Direct to Home (DTH), contribution, VSAT (Very Small Aperture Terminal) or DSNG (Digital Satellite News Gathering), but also to emerging markets such as **mobile applications**.

In fact, some of these new mobile applications considered within the new standard is high-speed trains, where several techniques such a spreading are allowed in order to deal with those scenarios with low SNR or with fast changes on SNR.

Some of the additional features added to the new DVB-S2X are:

- Smaller roll-off options are allowed (5% and 10% in addition to 20%, 25% and 35% in DVB-S2).
- It enhances physical layer signalling providing a finer granularity and extension of MODCODS (modulation and coding modes).
- Very Low SNR operation support down to -10 dB SNR
- Ability to configure the scrambling sequence (allowing systems to cope with high level co-channel interference in multi-satellite environments)

### 6.4.2 DVB-RCS / RCS2 / RCS2+M

In parallel to DVB-S (originally created for video broadcast), a specification for an interactive on-demand multimedia satellite system appears in the late 90s, the DVB-RCS (*Digital Video Broadcasting – Return Channel via Satellite*). DVB-RCS is a technical standard that defines a complete specification for two-way interactive satellite broadband communications. Depending on each deployment (link budgets and other design parameters) DVB-RCS can provide tens of Mb/s to terminals on the downlink, and typically few Mb/s from each terminal on the uplink.

A DVB-RCS network is a satellite-based communications system that provides interconnection between users who are exchanging real time applications based on several data types (*e.g.* text, voice, images, video etc…). There are two transmission paths, the Forward Channel from a centralized Hub location to the remote location and a Return Channel from the remote location to the central Hub.

Despite DVB-RCS has the benefits of being a very mature and well known standard scheme (*e.g.* multiple COTS equipment available, reliable technology, etc), it is not a specific solution for mobility (originally it was a non-mobile standard), which is reflected in the lack of options for mobility that are already available in other standards. This way, and despite it is not prepared for railway mobile channel, it has been used in several projects/trials for non-safety railway applications (with some modifications in order to overcome railway channel impairments), such as Mowgly or 21Net.

The core of DVB-RCS (and subsequent extensions and generations) is a multi-frequency Time Division Multiple Access (MF-TDMA) transmission scheme for the return link, which provides high bandwidth efficiency for multiple users.

Subsequently to this first RCS version, an enhanced version (in fact an extension) of the DVB-RCS was the DVB-RCS+M, which includes options for mobile channels.


Figure 40: Evolution of the Return Channel via Satellite

DVB-RCS+M was an enhanced version (actually an extension) of the former DVB-RCS to include options for mobile channels, being able this way to take into account aspects such as periodic fadings on railway channel due to power arches (or posts with horizontal brackets) and catenaries, for example. For that reason spreading was includes into this extension, and also a continuous carrier (CC) mode based on DVB-S2 waveform.

After last version of DVB-RCS (extension +M), a second generation of this standard was created, the DVB-RCS2, published in 2011. It included many improvements such as the ACM (*Adaptive Coding and Modulation*) within the return channel, complementing this way the ACM of the forward link (by means of the DVB-S2). This way, with this new improvement the use of this standard within higher frequency bands (such as Ka) was enabled (making possible the use of ACM in forward and return). This RCS2 added 16 new state turbo codes in addition to additional modulation schemes, providing this way better performance for mobile channels such as railway.

This second generation of the RCS standard also provides a Random Access (RA) return link access method. Therefore, it is not required to request capacity in advance (a good access method when data to be transmitted is intermittent and typically represents a small capacity).

Finally, a new mobile extension to RCS2 (*i.e.* DVB-RCS2+M) is ready to serve professional, commercial and governmental markets since 2012. It adds support for mobile/nomadic terminals and direct terminal-to-terminal (mesh) connectivity. DVB-RCS2+M features include live handovers between satellite spot-beams, spread-spectrum features to meet regulatory constraints for mobile terminals, and continuous-carrier transmission for terminals with high traffic aggregation. It also includes link-layer forward error correction, used as a countermeasure against shadowing and blocking of the satellite link.

### 6.4.3 DVB-SH

In addition to DVB-S/S2/S2X and DVB-RCS/2 standards family, there exist some other standards with different purposes, such as the DVB-SH (*Digital Video Broadcasting – Satellite services to Handhelds*), derived from previous DVB-H and ETSI SDR. It was created around 2007 with the aim of delivering IP base media content (video/audio) and data to handhelds terminals and vehicles based on hybrid satellite/terrestrial forward link. Due to the use of small terminals (handhelds), a low frequency band were thought to be used with this standard, just like the S-band.

Since DVB-SH are based on hybrid satellite/terrestrial systems, it allows the use of satellite to achieve coverage of large areas. And in areas where there is no satellite coverage, a terrestrial gap filler can be used seamlessly to provide coverage.

DVB-SH defines two different schemes:

- SH-A: based of OFDM (*Orthogonal Frequency Division Multiplexing*) for both satellite and terrestrial links
- SH-B: based on TDM (*Time Division Multiplexing*) only on the satellite link (and OFDM for the terrestrial link)

OFDM is a powerful modulation method that divides a high data rate modulating stream into many slowly modulated narrowband close-spaced subcarriers, making this way the signal less sensitive to frequency selective fading. OFDM has become a mature technique implemented in several systems such as WiMax, DVB-T or LTE.

Main advantages of OFDM are related with its ability to cope with severe channel conditions, such as:

- Spectrum efficiency, using orthogonal overlapping subcarriers
- Immunity to selective fading due to multipath
- Resilience to interference, since interference appearing in a channel will not affect all the sub-channels.
- Etc

The main disadvantage of OFDM is the high PAPR (*Peak to Average Power Ratio*) that may occur.

Therefore, DVB-SH is an interesting standard since its hybrid satellite/terrestrial solution eases the implementation of gap fillers. But as weak points, the few number of modulations and coders to fight against channel impairments and the use of its high flexible channel interleaver (that offers time diversity from about one hundred milliseconds to several seconds), which helps to signal recovery at receiver side but introducing a big delay not allowed by critical applications.

Another weak point of DVB-SH is the absence of commercial solutions (*i.e.* equipments), and even of satellite, since in April 2009 the W2A satellite was launched after Inmarsat and Solaris Mobile (a joint venture between Eutelsat and Astra) were awarded each a 2×15 MHz portion of the S band by the European Commission.

### 6.4.4 S-MIM

S-MIM (S-band Mobile Interactive Multimedia) is a radio interface standardized by ETSI. It is especially designed to provide messaging services over S-band GEO satellites.

Since S-band satellites are planned for the mobile broadcast of multimedia content to handhelds or vehicle-mounted mobile devices, the main goal of this standard is to get low power (low-cost) terminals and high bandwidth efficiency.

The forward link defined by S-MIM uses the DVB-SH as a broadcast radio interface. For the return link, S-MIM system provides 3 sets of service segments:

- SS1) Broadcast and interactive services
- SS2) Data acquisition services
- SS3) Real time (emergencies) services

The return link air interface is based on 2 non-exclusive options, depending on the service required:

- Asynchronous access using spread spectrum ALOHA (SSA), similar to ANTARES. First deployment was carried out in European project called SAFETRIP.
- Synchronous access using quasi-synchronous code multiple access (QS-CDMA).

Despite this standard is assuming S-band payload of a GEO satellite, non-GEO satellites are also compatible provided that Doppler compensation mechanisms are put in place. Therefore, other frequency bands such as L-, C- or Ku/Ka- bands might also be considered.

### 6.4.5 ANTARES CS

The European Space Agency (ESA), in coordination with SESAR Joint Undertaking and the European Organization for the Safety of Air Navigation (Eurocontrol), initiated the Iris programme to develop a satellite-based communication system and to standardise a new communication solution specifically designed for the provision of safety aeronautical Air-Ground communications in accordance with the future SESAR Air Traffic Management (ATM) concept. The new Communication Standard (CS) was developed in the frame of the ANTARES (AeroNauTicAl REsources Satellite based) project, which was part of the Iris programme. The satellite-based Communication Standard is able to cope with future Air Traffic Control (ATC) and Airline Operational Control (AOC) communication needs, allowing seamless operation with terrestrial standards.

Taking into account that the commonalities regarding safety features from both type of communication systems (*i.e.* railway and ATM), it is considered relevant to analyse this communication standard in the scope of this project in order to identify if it can be adopted in railways, although some modifications could be required.

This satellite Communication Standard was focused on the design of the physical and link layers (also called bearer) that provided the desired performances to cope efficiently with the ATM communications requirements.

The specific characteristics of the aeronautical communications have been the design drivers for the new Communication Standard (CS), namely:

- stringent Quality-of-Service (QoS) requirements (continuity, integrity and latency)
- L-band aeronautical mobile propagation channel (characterized by multipath effects),
- limited L band spectrum resources,
- bursty traffic generated by a large population of aircrafts (consisting of a short packets with low mean data rate),
- aircraft mobility (with speeds up to 2.5 MACH and maximum accelerations of 50 m/s),
- support of any aircraft type flying under Instrument Flying Rules (IFR) (fixed and rotary-wing aircraft). It is worth to notice that rotary wing is causing degradation (*i.e.* shortcuts or fast fading) similar to the catenaries post along the rail track.
- support of aircraft manoeuvres which can lead to fast degradations of the propagation channel.
- Besides, the new CS has been conceived to be compatible with multiple satellite orbital configurations, in particular, Geostationary orbit (GEO), Highly Elliptical Orbits (HEO) and Medium Earth Orbits (MEO) in order to ensure a global coverage including the Polar regions.

Most of these drivers are also applicable to railway domain and some of them are indeed more stringent than required in the railway critical applications.

This communication standard specifies the Medium Access Control (MAC) and physical layer of both, Forward and Return links.

In particular, the **forward link** is based on a **Multi-Frequency Time Division Multiple Access** (**MF-TDMA**) access scheme, which allows an efficient support of distributed Ground Segment (GS) with a high number of Ground Earth Stations (GES) sharing forward link carriers. The new Communication Standard foresees several mechanisms to counteract the aeronautical propagation channel impairments, such as channel interleaving, use of pilot symbols and adaptive Coding and Modulation (**ACM**)

Concerning the **return link**, an **Asynchronous-Code Division Multiple Access** (**A-CDMA**) scheme is proposed in which the traffic from active aircraft is transmitted by means of asynchronous packets with low channel baud rates from 1.25 kbauds up to 2.5 kbauds depending on the selected waveform configuration. The Physical Layer relies on the 3GPP W-CDMA technology (spreading based on OVSF and complex scrambling codes) while RA is based on the Enhanced Spread Spectrum ALOHA

(E-SSA) scheme. On the receiver side (Ground Segment), overlapped bursts from multiple user transmissions are recovered thanks to the iterative Successive Interference Canceller (SIC) algorithm. The SIC is able to exploit the inherent power unbalance among user transmissions in order to improve the spectral efficiency, throughput and system capacity.

The advantages of using A-CDMA scheme with E-SSA ([RD-09], [RD-10]) and iterative SIC at the receiver for M2M applications are the following:

- The A-CDMA scheme permits a system using Full frequency reuse among different beams, increasing dramatically the system efficiency.
- The User Equipment accesses to the channel in an asynchronous manner, not requiring any complex network synchronization mechanism.
- No power control mechanism is required to keep the User Equipment transmissions balanced. In fact, the use of an iterative SIC at the receiver allows to exploit the inherent power unbalance among User Equipment transmissions.
- The adoption of a CDMA-based scheme provides inherent robustness to multipath propagation channels, in special those propagation channels with more than one tap (*e.g.* aeronautical fading channel model).
- It supports efficiently the transmission of delay sensitive-short and long packets.
- It is able to achieve a spectral efficiency higher than 1 b/s/Hz with a target PLR of 1e-3.

# 7. SATCOM FOR RAILWAY COMMUNICATIONS CONSULTATION PROCESS

This section presents the results of the *SATCOM on the Move (SOTM) & Trains Survey*, carried out during October-November 2016. The methodology and other survey metadata are presented first, followed by the statistical analysis of the responses and the main conclusions that can be drawn thereof.

It is interesting to point out that inputs received, results and conclusions of this task have been taken into account in subsequent tasks of the study, such as the assessment and the conclusions and recommendations.

## 7.1 INTRODUCTION

The objective of the SOTM & Trains Survey was, first, to ascertain the state-of-the-art of SATCOM solutions and technologies, and second, to identify the current technology trends and gaps. The results of this study were expected to provide inputs for the decision making process on the inclusion of SATCOM technologies as part of the evolution of the railways radio communication system.

The design of the Survey took into account two important issues:

- **General aspects**. In order to ensure a high participation, the survey was designed maximising simplicity and minimising the time required to answer, while not preventing participants to express more detailed opinions, suggestions, etc. if they considered it appropriate. The language used in the survey and in the invitation letters was conversational, also aiming at increasing participation.
- **Sensitive information**. Some of the questions, notably those related to planned products and support for future standards, tackle sensitive subjects that might be of strategic/commercial importance for the consulted companies, so some reluctance to participate was envisaged. It was deemed important to stress, when asking those questions, that they are to be answered only on a voluntary basis, so that at least partial feedback could be obtained.

### 7.1.1 Targeted stakeholders

The SOTM & Trains Survey targeted various groups of stakeholders:

- Satellite communications stakeholders:
  - Component manufacturers and integrators
  - Satellite operators
  - Space agencies (ESA)
- Railway communications stakeholders:
  - Railway Undertakings (RU)
  - Infrastructure Managers (IM)
  - Train/trackside equipment manufacturer
  - UIC ATWG (Architecture and Technology Working Group)
- Communications service providers and mobile network operators

For each group of stakeholders, a number of companies and individuals were identified and contacted. Examples of respondents are shown in Table 24.

| Group | Respondents | Total invited |
|---|---|---|
| **SATCOM** | Airbus, Comtech, Govsat, Hispasat, iDirect, Inmarsat, Intelsat, Iridium, Newtec, SpaceCom A/S | 16 |
| **Railway communications and communications service providers (RAIL)** | Adif, Alstom, Ansaldo, Avanti, Bane Danmark, Deutsche Bahn, Funkwerk Systems, Kapsch CarrierCom, Nokia, Land Transport Chamber of Commerce, ÖBB Infra, PKP Cargo, ProRail, SNCF, Talgo, Trafikverket, UIC Future Railway Mobile Communications System, including Orange, Infrabell, Systra and SBB. | 37 |

Table 24: Targeted stakeholders: examples of respondents

When multiple responses were obtained from a single response per company/organisation, a single one was considered, in order not to bias the results.

### 7.1.2 Survey questions

The full set of questions in the Survey can be found in Annex §B, and were categorised in several groups:

- Trends and new developments
- Operational issues
- QoS performances
- GSM-R evolution framework
- Use of SATCOM for business applications

### 7.1.3 Survey presentation

Responses to the Survey were gathered from a Word questionnaire, as well as from an online form.

The Word questionnaire is included in Annex §B, and was common to all targeted stakeholders.

As for the online channel, the tool of choice was Typeform (www.typeform.com), a *freemium* offering that features very simple administration and setup, extremely easy-to-follow surveys with full mobile support, and comprehensive analytics. The following figures show some examples of the survey design as it was presented to the users.


Figure 41: SOTM & Trains Survey: introduction page

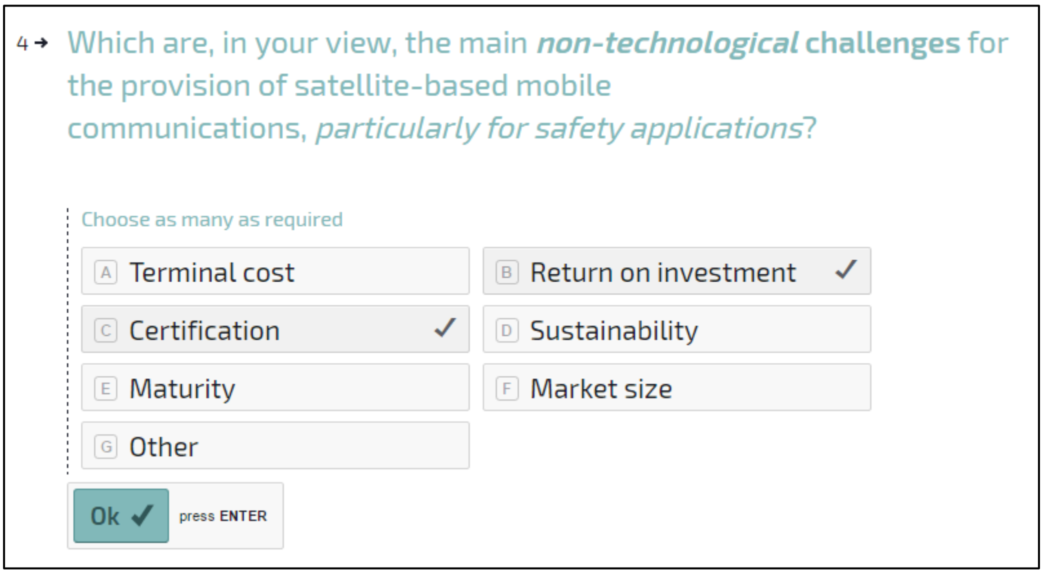



Figure 42: SOTM & Trains Survey: multiple-choice answers

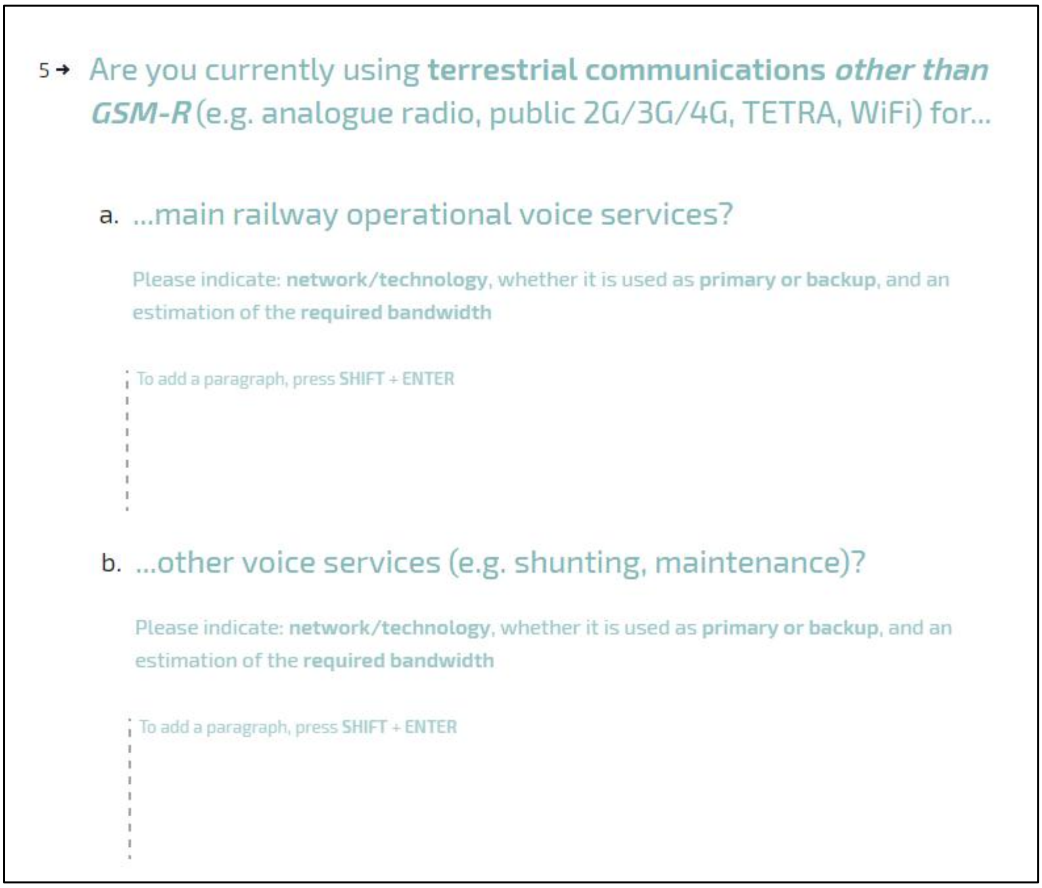



Figure 43: SOTM & Trains Survey: question groups

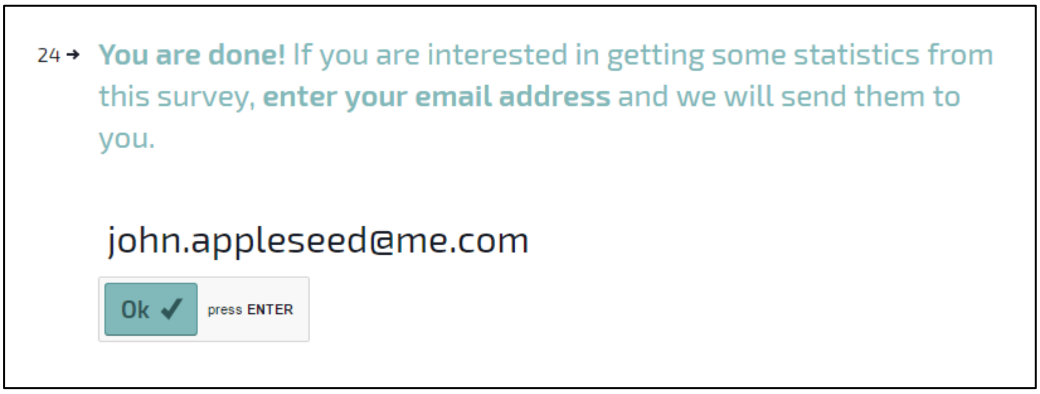



Figure 44: SOTM & Trains Survey: closing page (with prompt for follow-up email)

The survey was split in two, depending on the targeted stakeholder:

- For SATCOM stakeholders: https://indra-satcom-surveys.typeform.com/to/pH1Po5
- For other stakeholders: https://indra-satcom-surveys.typeform.com/to/fb8Md3

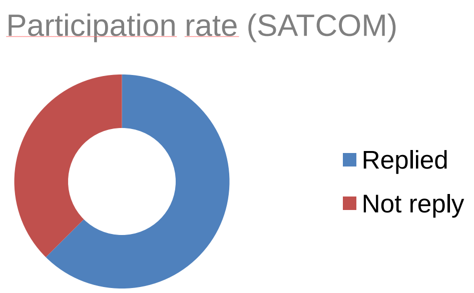
## 7.2 SURVEY RESULTS

### 7.2.1 Overview

Table 25 summarises the participation rate for the various stakeholder types targeted by the Survey (see also Figure 45).

| Group | Invited | Responded | Participation rate |
|---|---|---|---|
| **SATCOM** | 16 | 10 | 62.5% |
| **RAIL** | 37 | 21 | 56.8% |
| **Total** | 53 | 31 | 58.5% |

Table 25: Participation rate per stakeholder type



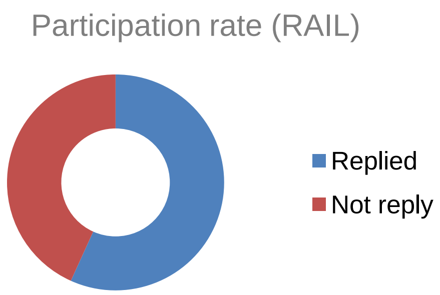




Figure 45: Participation rate

Around half of the responses (56%) were received through the **online questionnaire**.

The following sections summarise the responses obtained for the various Survey questions.

### 7.2.2 Questions for SATCOM stakeholders

#### 7.2.2.1 Trends and new developments

Figure 46 shows the **main trends** identified by the participants in the area of SOTM. Most of them attributed great importance to improving antenna profile and performances, followed by increased data rates. By contrast, none or very few respondents chose handheld support, lower spectrum bands or proprietary communications protocols among their identified main trends.

Other responses (not shown in the figure) included:

- Improved availability (not necessarily higher data rates)
- Electronically steerable flat-panel antennas

A participant elaborated on the fact that HTS is a key enabler behind great innovation on the ground, in particular enabling the substantial improvements to antenna profile and performance.

Finally, several participants indicated that LEO/MEO orbits are indeed a trend, albeit a longer-term one.

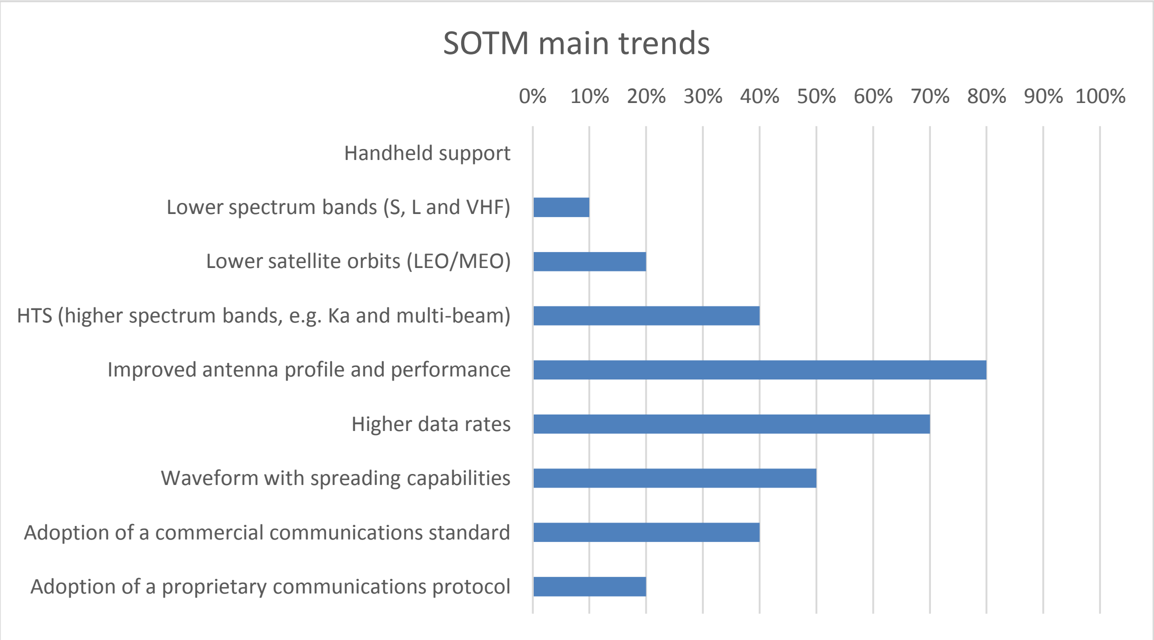



Figure 46: SOTM main trends

When asked about the main **technological challenges** for SATCOM in safety applications, multiple responses are given (see Figure 47), with the highest-ranked challenge being antenna dimensions, or form factor. Other responses included:

- Throughput and latency performances
- Reliability
- Competitiveness (with respect to ground-based solutions)
- Coordination of beam switching in large, complex global networks with multiple overlapping beams

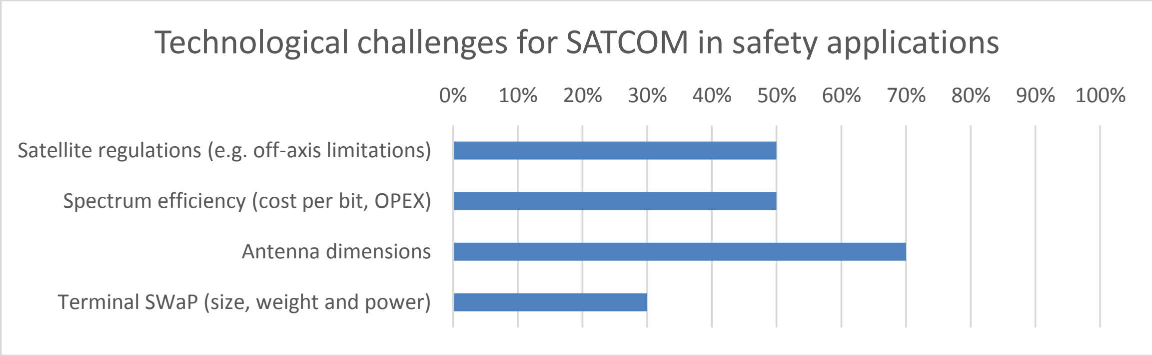



Figure 47: Technological challenges for SATCOM in safety applications

Regarding the **non-technological challenges** for SATCOM in safety applications, return on investment emerges as the clearer winner (see Figure 48). Some participants also highlighted:

- The perception that SATCOM is complicated and costly (and the need to change that public perception)
- The niche status of SATCOM solutions
- The fact that SATCOM is still relatively immature, in comparison with more established ground-based technologies
- The downward trend in OPEX costs (thanks to next-generation HTS satellites)

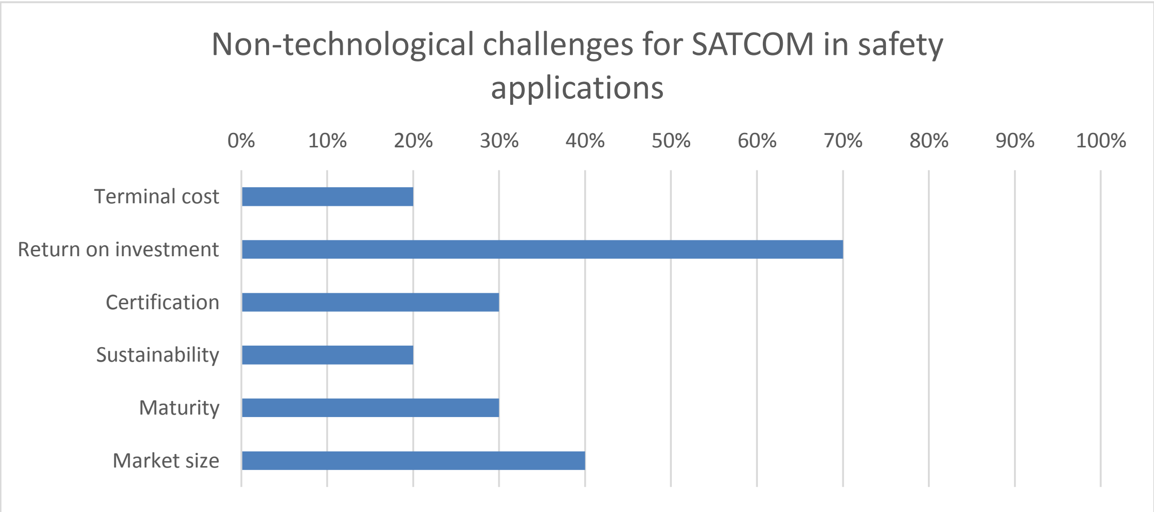



Figure 48: Non-technological challenges for SATCOM in safety applications

Finally, around half of the respondents chose network convergence (5G, in which SATCOM can be standardised) and ground-space bandwidth-sharing technologies as the **main drivers** for the adoption of SATCOM in the railway domain (see Figure 49). Other insights from the participants included:

- SATCOM provides railway operators with > 99% availability (despite having higher latency than ground-based communications networks).
- Multi-service VSAT platforms can support a wide variety of vertical markets, driving synergies and economies of scale.
- Seamless interoperability between space and ground networks.

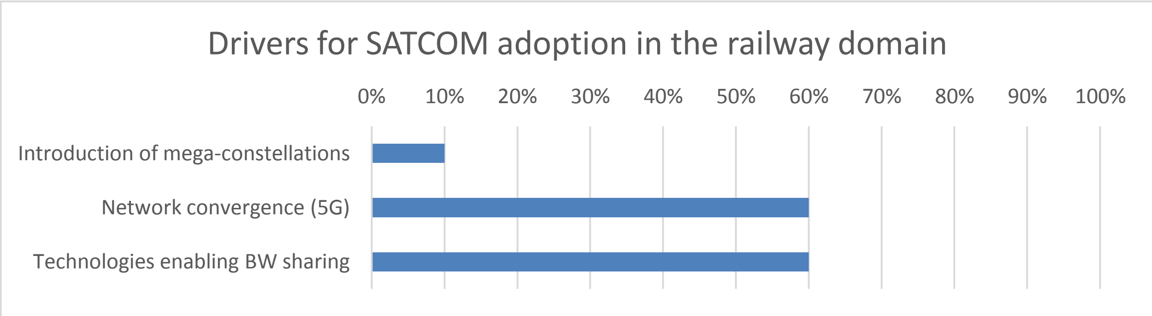



Figure 49: Drivers for SATCOM adoption in the railway domain

#### 7.2.2.2 Operational issues

According to the responses from the participants, the Ka **band** holds the most promise for tomorrow's SOTM systems, followed closely by the Ku band (see Figure 50). Some participants remarked that they would also consider providing L-band services, if a large enough opportunity arises.

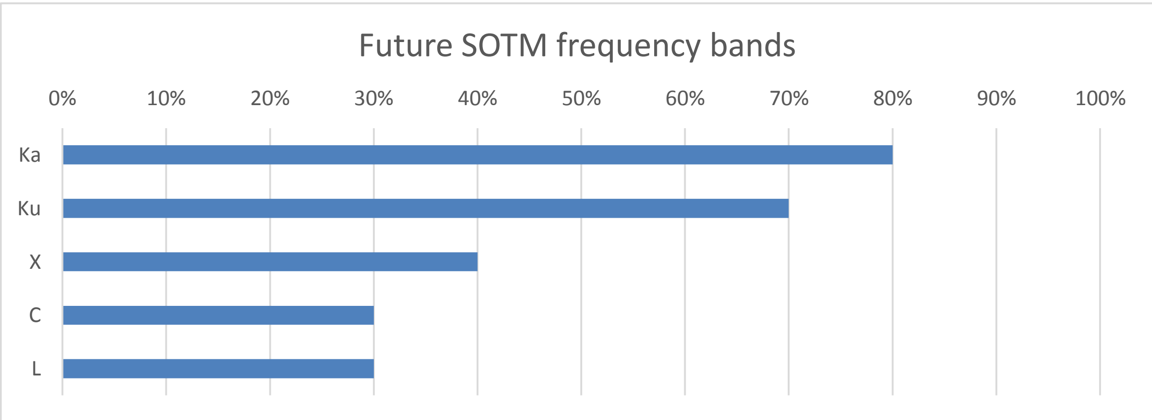



Figure 50: Future SOTM frequency bands

Regarding the **constellations** currently in use, GEO satellites are the clear winners (see Figure 51). MEOs and LEOs are also mentioned by some participants for the future, but they do not seem to be there yet (as also evidenced by the response to the "main trends" question in Section §7.2.2.1). Some respondents report holding off until a large enough opportunity appears, or having them in their roadmaps.

All participants confirmed that the constellations they use support **voice call services**, indicating that multi-party/conference features is feasible with current constellations.

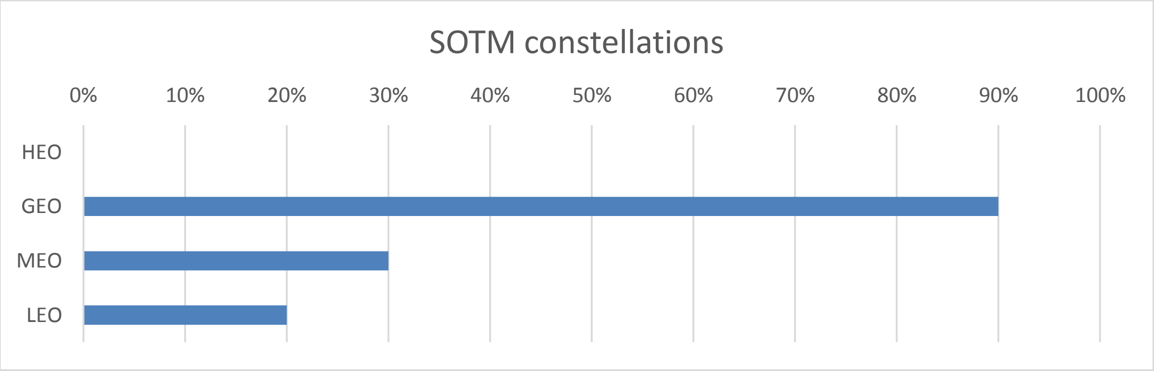



Figure 51: SOTM constellations

Finally, only 20% of the participants indicated that their products are **compliant with railway norm** EN-50155 (see Figure 52), lower even than those who could not provide an answer. When asked to provide more details about the railway norms their products complied with, most SATCOM respondents showed little or no specific conformance to such norms.

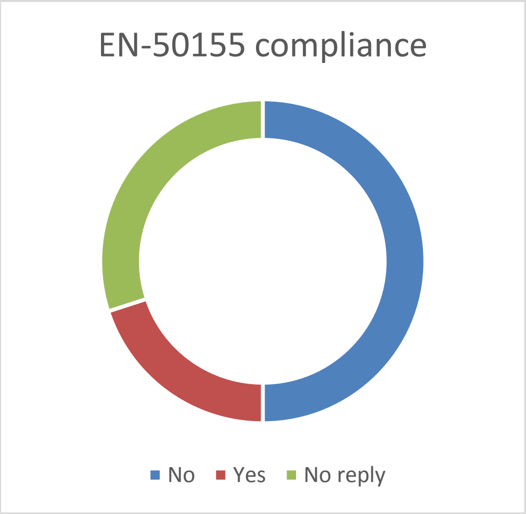



Figure 52: EN-50155 compliance

#### 7.2.2.3 QoS performances

Despite a low degree of conformance to railway-specific norms (see Section §7.2.2.2), most SATCOM providers report a high qualitative assessment on the **suitability of their products for the railway domain** (see Figure 53).

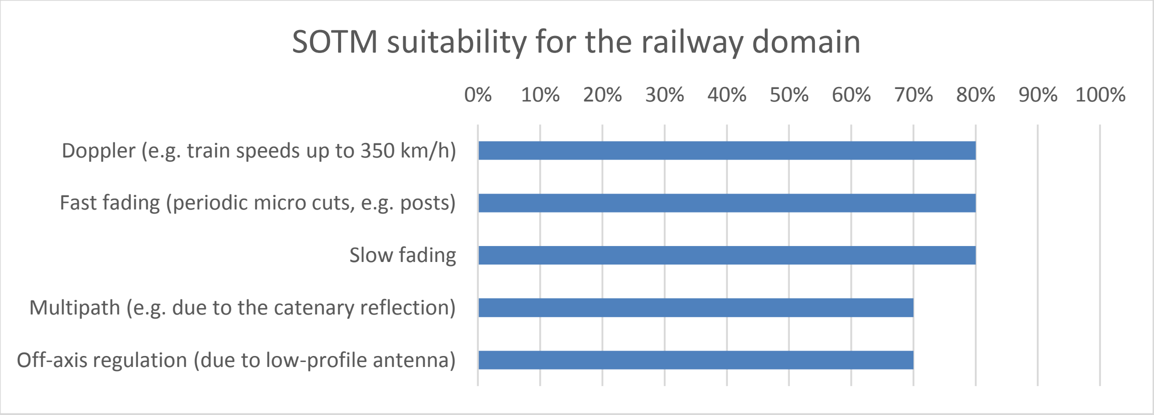



Figure 53: SOTM suitability for the railway domain

According to the Survey responses, most of the pieces of equipment for a SATCOM-based communications system in the railway domain are available from the manufacturers. All 4 categories of equipment (baseband, antenna/RF, constellation, ground stations) are provided by at least 3 of the surveyed participants. Current product lines include:

- Inmarsat BGAN, IDP and GX
- L-band tracking antennas
- Iridium Short Burst Data (SBD), RUDICS / Circuit Switched Data, Voice Service, PTT (Push to Talk), Broadband (Certus Services 22KB/s - 1.4MB/sec)
- Hispasat constellation, Indra-Aicox-iDirect next-generation system
- VT iDirect equipment
- Newtec Dialog VSAT platform hubs and modems / Newtec HUB6000 and MDM6000 modems

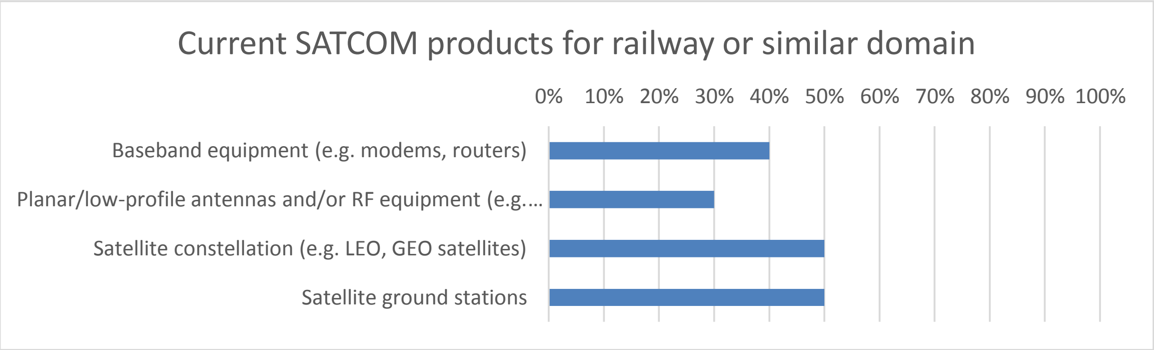



Figure 54: Current SATCOM products for railway or similar domain

When asked about the **air interface standards** they support, around half of the participants included DVB-S2 among their answers. Satellite operators reported support for whatever air interface service operators work with, but confirmed the predominance of the DVB family of standards). Two equipment manufacturers also indicated working with either proprietary interfaces, or subsets of DVB standards.

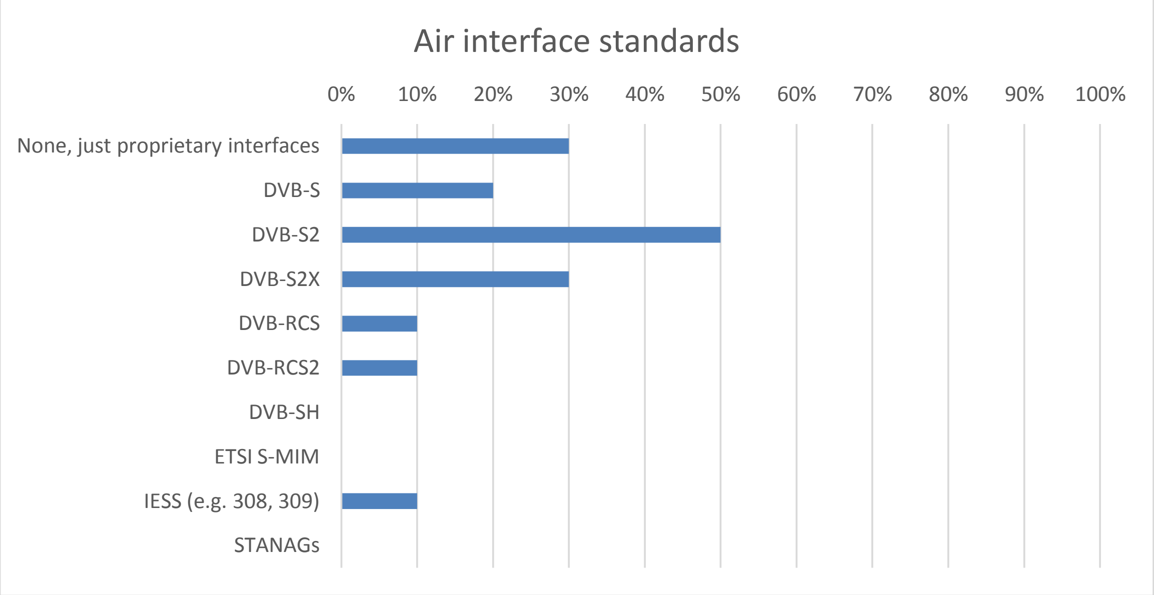



Figure 55: Air interface standards

Regarding the **features provided by current SATCOM systems** that address specifically SOTM's characteristics and channel impairments, the most frequent response included enhanced FEC schemes (70% of the responses), signal spreading (60%) and fast signal acquisition techniques (60%). Notably absent from the results were LL-FEC and ARQ techniques.

Other responses included:

- OpenAMIP: a protocol to exchange information and commands between modem and Antenna Control Unit for antenna pointing (2 respondents)
- Automatic initial beam selection and beam switching, Doppler resilience, dual demodulators for seamless beam switching

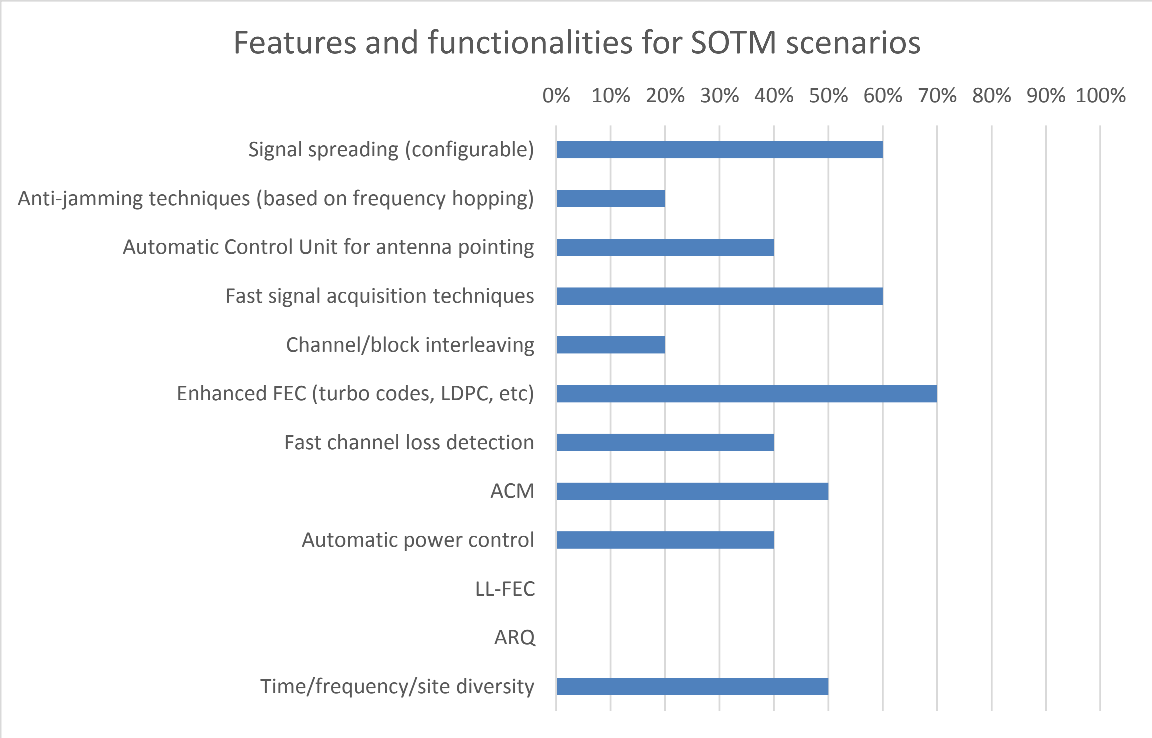



Figure 56: Features and functionalities for SOTM scenarios

When asked about the **services offered or intended to be offered for mobile scenarios** (not necessarily for safety communications), most of the participants showed an extensive portfolio of technologies and services:

- BGAN, IsatPhonePro2, IsatHUB
- Short Burst Data (SBD), RUDICS / Circuit Switched Data, Voice Service, PTT (Push to Talk), Broadband (Certus Services 22KB/s - 1.4MB/sec)
- Internet, VoD, TV multicast and other onboard entertainment services
- SCPC, MESH and STAR (MCPC) solutions
- RPAS / UAV / Maritime applications
- Remote and Hub equipment
- IntelsatOne Flex (for high-performance COTM/SOTM in rail, aviation, maritime and automotive environments); intended: integration of LEO service from OneWeb (upon availability)
- Turn-key solutions for mobile SATCOM

Regarding the provision of **services for safety communications**, 70% of the respondents stated that they either provided them already or intended to do so in the future (see Figure 57). Among those that replied affirmatively, some provided more details on the current/intended services:

- GMDSS for maritime; SwiftBroadBand (SB) Safety for aviation
- GMDSS for maritime; Aireon for aviation; other safety services for oil and gas workers (safety, duty of care, etc.)
- Governmental/defence services (in the future)
- Safety services, often combined with crew welfare and corporate communications services

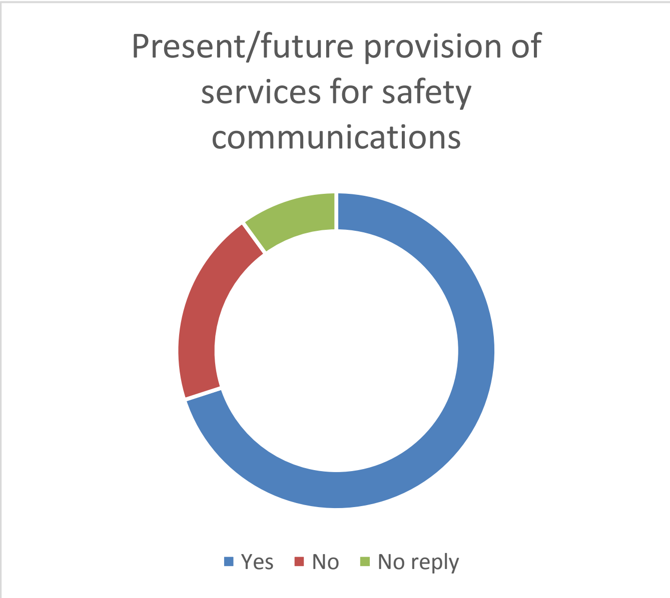



Figure 57: Present/future provision of services for safety communications

Finally, participants were asked whether their SATCOM solutions support the **use of handhelds** or so-called satphones. 60% of the respondents answered affirmatively.

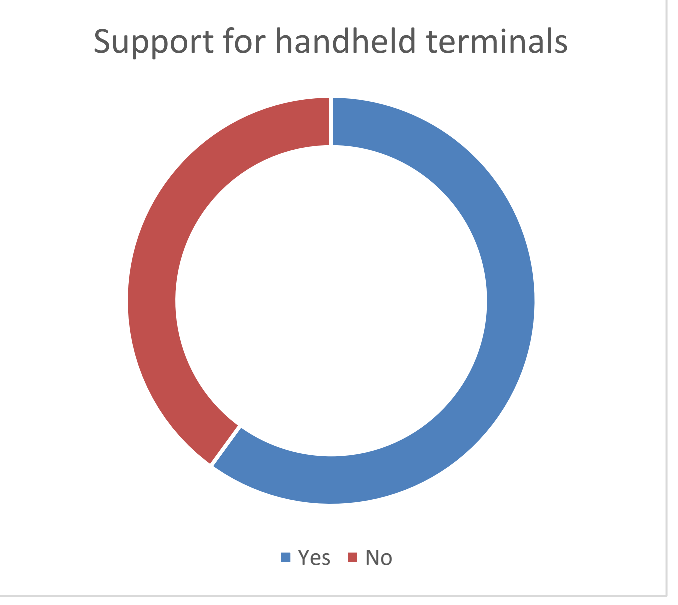



Figure 58: Support for handheld terminals

### 7.2.3 Questions for railway stakeholders

#### 7.2.3.1 GSM-R evolution

Most of the Survey participants reported belonging to working **groups dedicated to railway communications**:

- UIC (ERIG, FM WG, FRMCS…)
- GSM-R Industry Group
- ERTMS
- ETSI (NG2R)
- SHIFT2RAIL X2RAIL-1 WP3 and CONNECTA WP2
- TCNOpen
- ROC Industry Group
- Agency WP/WGs
- 3GPP
- EUG Security WG
- EUAR
- EIM
- CER Control-Command & Signalling Support Group

Furthermore, **awareness of ongoing initiatives** for the replacement of GSM-R scored high (see Figure 59), with the exception of ESA ARTES projects.

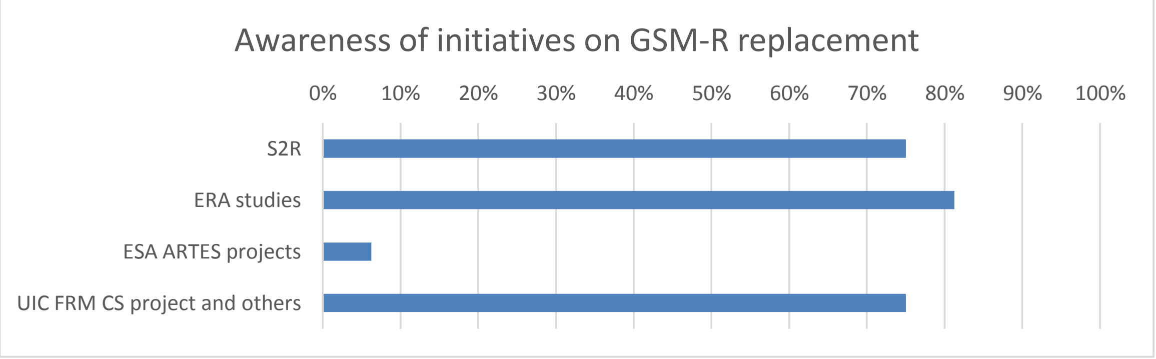



Figure 59: Awareness of initiatives on GSM-R replacement

According to the participants, **GSM-R is currently in use mostly for** ETCS Level 2 data and operational voice services (see Figure 60). Other uses, such as other voice services and non-critical data, ranked significantly lower. Some participants reported further uses, such as timetable downloads.

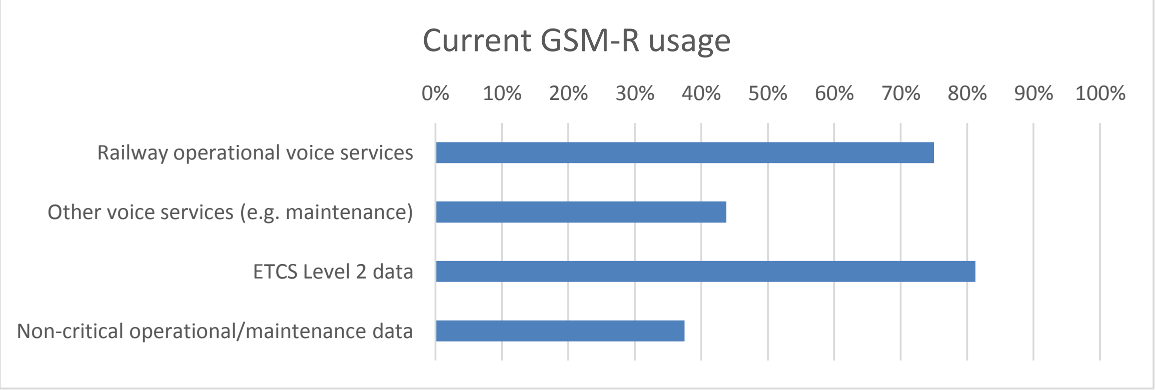



Figure 60: Current GSM-R usage

Respondents also described their current **use of networks other than GSM-R** for a variety of railway functions and services (see Table 26). Only in a few cases was SATCOM mentioned:

- In a particular Australian freight line (usage undefined)
- Under test, along with advanced multi-bearer solutions involving both SATCOM and public 3G/4G networks
- On particular lines (*e.g.* Thalys) for passenger services

| Function/service | Typically used networks |
|---|---|
| **Main railway operational voice services** | 2G/3G/4G, GSM-R GPRS, WiFi, analogue radio |
| **Other voice services (e.g. shunting, maintenance)** | 2G/3G/4G, GPRS, WiFi, analogue radio, TETRA |
| **Train protection and signalling** | GPRS (EDGE), ISDN ETCS 4+, MPLS IXL 100, wireline |
| **Other non-critical data** | 2G/3G/4G, GPRS (EDGE), WiFi, analogue radio, private optical/SDH, |
| **Passenger services** | 2G/3G/4G, WiFi, proprietary solutions (NOMAD, ICOMERA, 21Net…) |

Table 26: Use of networks other than GSM-R in the railway domain

When asked specifically **whether they currently used SATCOM**, most responses were negative, except in the cases described above. Affirmative respondents cited differences in service availability as the main drawback of SATCOM (31% of respondents), followed by QoS and performance (25%).

Looking into the future, around half (56%) of the respondents showed **interest in 4G/LTE as the main platform for future** railway communications. The remaining participants were mostly supportive of multi-bearer systems, involving WiFi, shared networks with other emergency/critical services, 5G and SATCOM.

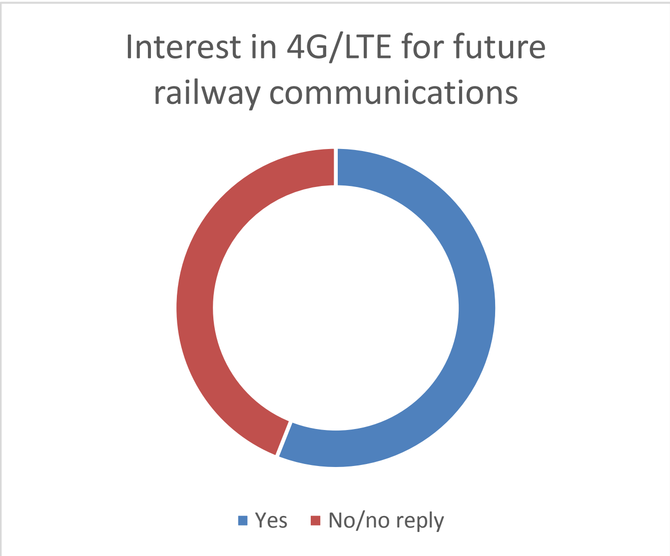



Figure 61: Interest in 4G/LTE for future railway communications

Around two-thirds of the participants indicated that **they had already taken steps in preparation of future railway communications systems**. Of those, most cited participation and contribution to design and standardisation Working Groups, experimentation with new technologies, and increased support for multi-bearer solutions. Some also cited contacts with their national spectrum regulators.

Asked about the **role of SATCOM in future** railway communications, there exists high consensus that SATCOM could make sense as either a backup system, a complement for coverage gaps or backhaul, or as part of a hybrid, multi-bearer solution. No respondent believed that SATCOM could be used in an isolated way.

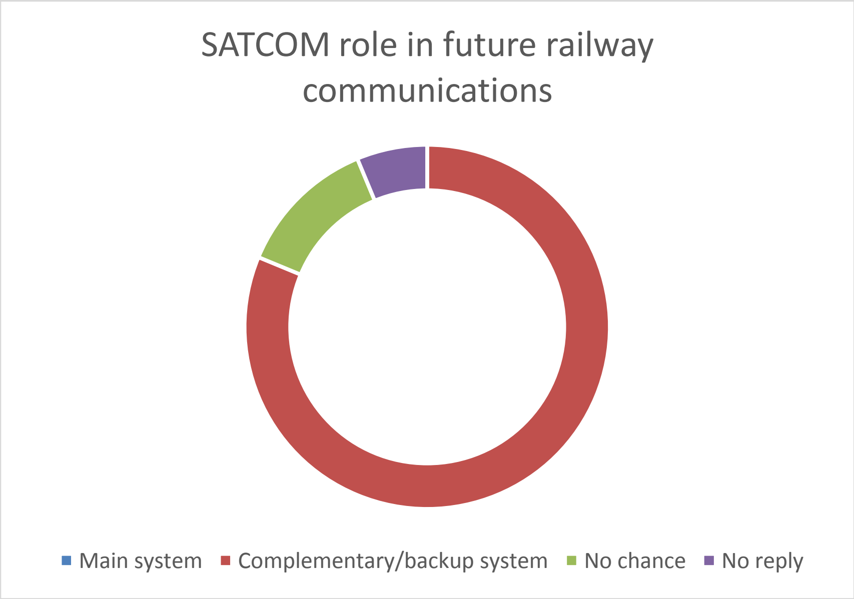



Figure 62: SATCOM role in future railway communications

Participants were also asked about potential SATCOM usage in various scenarios:

- **Main stations/shunting yards** (lots of users, low speed): 34% of the respondents considered SATCOM useful in this scenario.
- **Dense/urban lines** (lots of users, moderate speed): only 27% of the respondents considered SATCOM useful in this scenario, taking into account the required capacity.
- **Low-density/regional lines** (limited number of users, moderate-to-high speed): contrary to the previous scenarios, 80% of the respondents found SATCOM suitable for this scenario, provided that a suitable target availability requirement was met.
- **High-speed lines** (limited number of users, very high speed): around 33% of the respondents found SATCOM useful in this scenario, despite the fact that high speed would affect such a system to a less degree than terrestrial solutions.

Asked about their **concerns for using SATCOM in the railway domain**, the most cited factor (see Figure 63) was service availability, or more accurately the lack thereof along the line (75%), followed by QoS/performance issues (63%) and high CAPEX (44%).

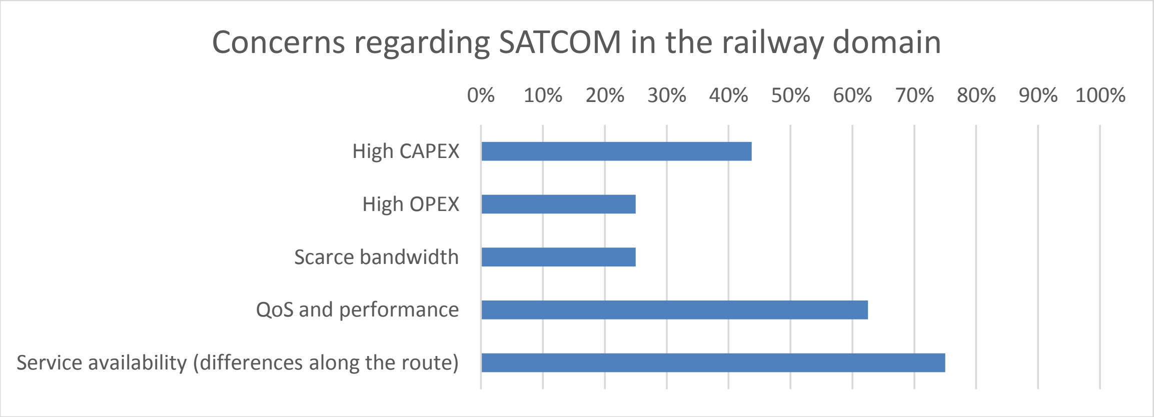



Figure 63: Concerns regarding SATCOM in the railway domain

### 7.2.4 Common questions

This section summarises the responses to common questions asked to both SATCOM and RAIL stakeholders.

#### 7.2.4.1 SATCOM in the railway domain

Asked about **certification hurdles** (see Figure 64), participants cited predominantly conformance to EN-50155 and train installation verification, although the former scored higher among SATCOM stakeholders, as might be expected, and the later among RAIL stakeholders. Non-predefined responses included:

- Antenna installation on the roof of the train
- Security aspects
- Required MTBF levels
- Form factor
- Regulatory restrictions and licensing

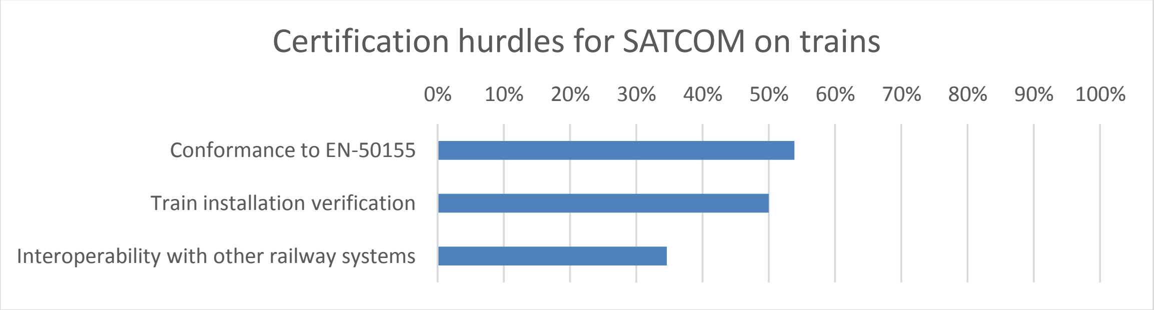



Figure 64: Certification hurdles for SATCOM on trains

Regarding the **main problems for SATCOM adoption on trains** (see *Figure 65*), respondents seemed more concerned about SATCOM performances (coverage gaps, 65%; latency constraints, 62%) than about its cost, being OPEX one of the strong added values of this solution.

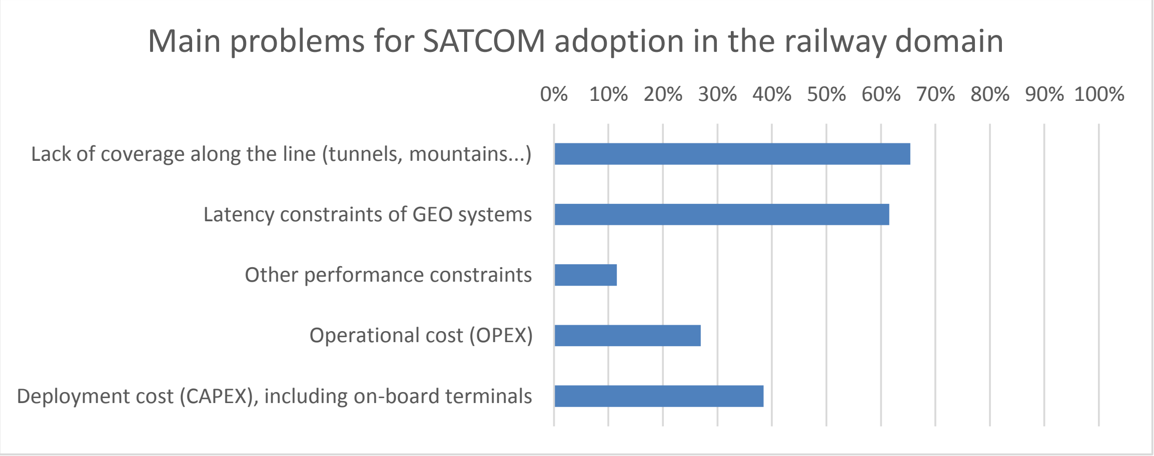



Figure 65: Main problems for SATCOM adoption in the railway domain

#### 7.2.4.2 Use of SATCOM for business applications

The possibility of using SATCOM for business applications in the future railway communications system was perceived predominantly as positive (see Figure 66), whereas around half of the respondents believed that it made economic sense (see Figure 67).

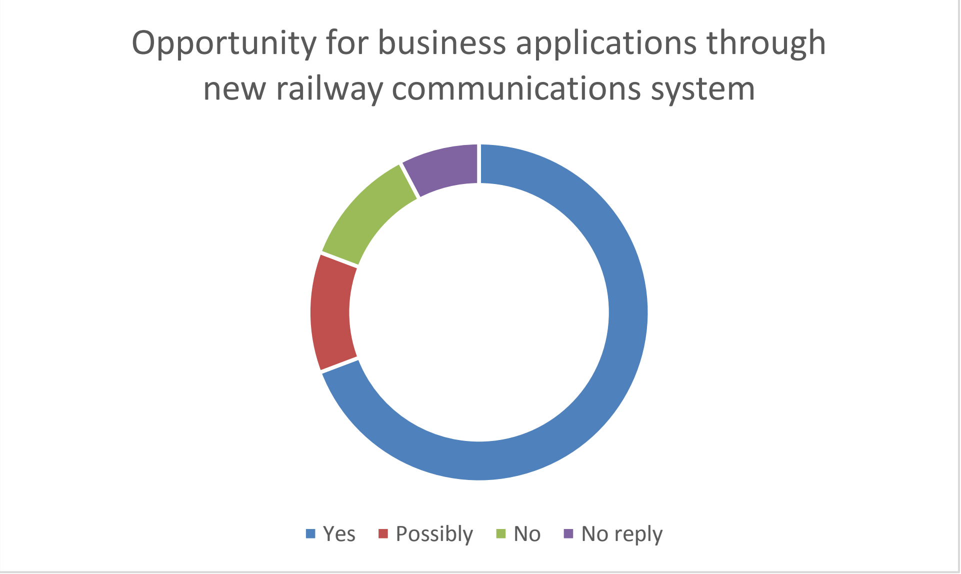



Figure 66: Opportunity for business applications through new railway communications system

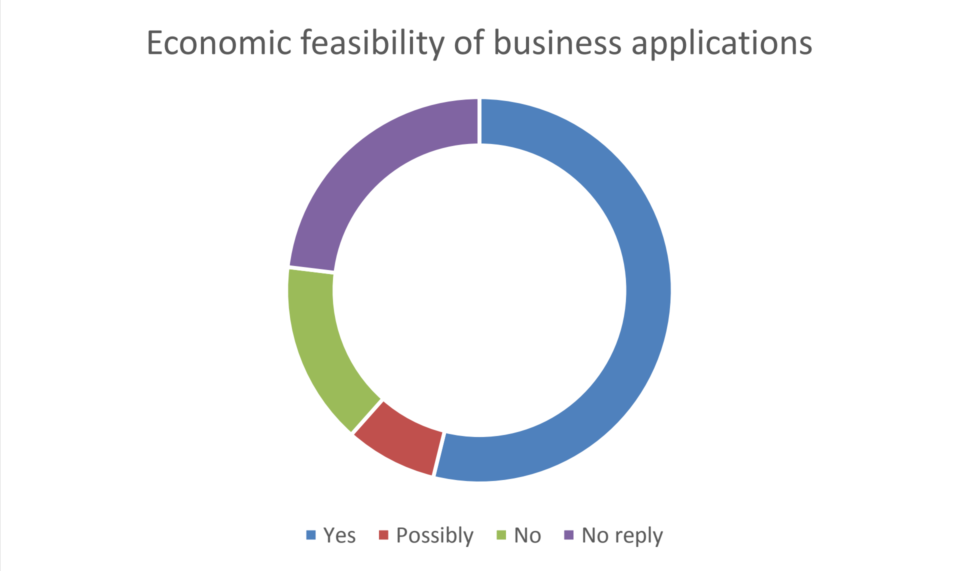



Figure 67: Economic feasibility of business applications

## 7.3 CONCLUSIONS

Section §7.2 provided a statistical analysis of the results from the SATCOM on the Move & Trains Survey. Participation to this Survey was relatively high, with 26 responses from both SATCOM and RAIL stakeholders, and the following conclusions could be reached:

- **Awareness**: RAIL stakeholders are obviously well aware of the ongoing initiatives on GSM-R replacement and are well-represented in the corresponding standardisation bodies and Working Groups. Specific knowledge of SATCOM solutions is relatively low, with almost no awareness of ESA ARTES projects and little or no experience with SATCOM products, except in a few pilot lines and experimental activities
- **Overall technological suitability**. Few SATCOM products are currently certified for the railway domain, be it EN-50155 or other railway-specific norms. However, the perception among SATCOM providers is that current SOTM products are suitable for this domain, with a majority stating compliance with the RF channel characteristics (Doppler, slow and fast fading, multipath and off-axis masks), even though antenna dimensions remain the main trend and technological challenge, in this as well as other mobile environments. Around 70% of the SATCOM providers stated that they either provided safety-oriented mobile services already or intended to do so in the future. On the other side, RAIL stakeholders cited irregular service availability along the railway line as their main concern regarding SATCOM solutions, followed by the latency inherent to GEO systems.
- **Handheld support**. There seems to be a key divergence in the way SATCOM and RAIL stakeholders look at handheld support. In the railway domain, such handhelds are taken for granted and supported by current communications systems (GSM-R, analogue radio). In the SATCOM domain, however, adding handheld support is conspicuously missing from SOTM

main trends. Except for systems that do provide such support (e.g. Iridium), other stakeholders are not actively working on it.

- **Voice support**. Even though data services are more and more important in the railway domain, voice remains a crucial requirement, especially for non-ETCS lines. Both kinds of services are offered by most of the surveyed SATCOM providers.
- **Cost aspects**. When asked about non-technological challenges for SATCOM in safety applications, most SATCOM participants cited return on investment as their primary concern, followed by market size. Consequently, most SATCOM providers would try to adapt existing technologies and constellations (typically, GEO satellites operating in Ku- or Ka-band) to the new domain, except if a large enough opportunity arises (e.g. for LEO/MEO satellites and/or L-band services). RAIL participants were relatively less concerned about CAPEX/OPEX in a SATCOM system, probably considering the cost of terrestrial systems.
- **Future role of SATCOM**. RAIL stakeholders consider unanimously that SATCOM cannot be the single, main solution for the future railway communications system. However, they mostly (81%) agree on the possibility that SATCOM may play an important role as *part* of it, either as a complementary system for some scenarios, a backup system, or a backhaul. SATCOM stakeholders would tend to agree, considering aspects such as network convergence (5G) and bandwidth sharing as the two main drivers for increasing SATCOM uptake in the railway domain.
- **Suitable scenarios for SATCOM**. According to 80% of the RAIL participants, SATCOM would be well-suited for low-density/regional lines, with a limited number of users and moderate-to-high speed. Other scenarios scored substantially worse among RAIL stakeholders: main stations/shunting yards (34%) and dense/urban lines (27%). The low value attributed in high-speed lines (33%) contrasts with the fact that SATCOM tends to cope better with high speeds than terrestrial solutions.

# 8. PRE-SELECTION OF SATCOM SOLUTIONS

In the previous section §6, several current and future SATCOM solutions (either underway, planned or simply evolutions of current systems) have been identified and described taking into consideration the 3 key elements of a SATCOM system (orbit, frequency band and air interface).

Before starting the assessment of the SATCOM solutions, **several of these solutions have been discarded** in advance by technical and/or non-technical reasons. Solutions discarded and their justifications are explained in Table 27.

| *Discarded SATCOM solutions* | *Justification* |
| --- | --- |
| Globalstar | Globalstar is not going to be analysed about its feasibility for railway communications because:<br>- It is a LEO solution which future evolution is not assured.<br>- Other LEO solution currently launching a new complete constellation evolution (*i.e.* Iridium) is going to be analysed. Therefore, conclusions about a LEO constellation can be drawn by means of Iridium. |
| ICO (MEO / S-band) | Despite technically this solutions is very attractive for railways communications, it is discarded in advance for several non-technical reasons:<br>- It is currently in disuse and arriving to its end of life.<br>- Its future evolution is not planned.<br>- A very similar solution (although theoretical) based also in a MEO constellation is going to be analysed (the MEO/C-band solution). |
| O3b (MEO / Ka-band) | O3b has been discarded in advance because:<br>- It has not been conceived for SOTM (Satcom On The Move), but for fixed terminals acting as backhaul.<br>- It does not provide coverage to the whole European area.<br>- Other "MEO" and "Ka-band" solutions are analysed (such as MEO/C-band and GEO/Ka-band). |

Table 27: SATCOM solutions discarded in advance

In addition, it is also worth mentioning that some of the solutions presented previously in section §6 and summarised in Figure 18 are going to be evaluated jointly. They are:

- *Inmarsat 4* (BGAN) and *Inmarsat 6* (ICE), since Inmarsat 6 is considered the future evolution of Inmarsat 4 and, in addition, there is no information available about this future system given that it is still on its design phase.
- *Inmarsat 5* (GX) and *GEO/Ka-band*, since GX is actually a GEO/Ka-band and communications standards used are based on DVB family.

Therefore, once SATCOM systems listed in Table 27 have been discarded for future railway communications and it has been explained that some solutions are going to be evaluated jointly, the list of pre-selected SATCOM solutions for their assessment as a future railway communications system is summarised in Table 28. These solutions cover ranges of possible values of satellite orbit, frequency bands and air interface, providing a broad vision of the SATCOM possibilities within the railway domain.

| SATCOM solutions | | | Description |
|---|---|---|---|
| LEO | 1 | Iridium NEXT | Iridium NEXT is a near-future LEO constellation (currently underway) that is going to replace the original Iridium constellation. With its 66 operational satellites, it provides full coverage to the Earth offering voice and data services.<br>Iridium NEXT operates the L-band (like the former Iridium) but also the Ka band to provide broadband services to fixed terminals. |
| MEO | 2 | MEO / C-band<br>(DVB-S2X – DVB-RCS2+M) | This solution is neither in development nor planning stage, but has been analysed since it was the most suitable candidate of the Satcom4Rail study [RD-02].<br>There exists a similar solution based on MEO/S-band (ICO), but it is reaching the end of its life cycle. |
| GEO | 3 | Inmarsat 4/6 (GEO / L-band) | Inmarsat 4 is a GEO / L-band solution that provides voice and data services worldwide with a current constellation of 3 GEO satellites[11].<br>Inmarsat 6 is set to become the evolution of current Inmarsat 4, including several improvements in performance and new services. |
| | 4 | GEO/L-band + ANTARES CS<br>(IRIS FOC) | It has been considered very interesting to analyse a GEO / L-band solution using a communication standard (CS) based on a pure random multiple access (just like the ANTARES CS, which was conceived to meet with Air Traffic Management requirements). It is assumed that the future IRIS FOC (developed under ESA program ARTES 10) is aiming to include similar features beyond 2025[12]. |
| | 5 | Thuraya (GEO / L-band) | This is an interesting solution since this system is able to provide coverage by means of a satellite system (GEO satellites operating at L-band) fully compatible with terrestrial GSM networks (increasing this way the availability required for critical applications). |
| | 6 | GEO / S-band<br>(S-MIM) | This solution is very similar to a GEO / L-band. Therefore, it will be analysed considering a different air interface than the previous GEO / L-band solutions. In this case, the S-MIM standard is taken into account. This standard was conceived for mobile applications supporting handhelds and enabling hybrid solutions combining satellite and terrestrial bearers. |
| | 7 | GEO / C-band<br>(DVB-S2X – DVB-RCS2+M) | Again, this solution will be similar to previous GEO / L and GEO / S bands. C-band provides more bandwidth than L and S-bands, but it is a higher band and it is more affected by weather conditions. This solution will be analysed with CS DVB-S2X in the forward link and DVB-RCS2+M in the return link. |

[11] It is taken into account the performances from SwiftBroadband (BGAN) service conceived for providing aeronautical services.

[12] According to SESAR Master Plan 2015

| | | | |
|---|---|---|---|
| | 8 | GEO / X-band (DVB-S2X – DVB-RCS2+M) | This solution, despite its similarity to the previous GEO/C-band, is interesting to be analysed since GovSatcom initiatives that are going to provide safety & security applications to the European members will take advantage of the military and governmental reserved bands (X-band and a portion of the Ka-band). |
| | 9 | SmartLNB (F-SIM) | Despite the fact that SmartLNB is based on GEO / Ku/Ka bands, it is very interesting to be analysed since its return link is based on the S-MIM CS, which relies on a pure random multiple access offering very narrow band services. |
| | 10 | GEO / Ku-band (DVB-S2X – DVB-RCS2+M) | This solution is similar to the SmartLNB system regarding orbit and frequency band. But in this case it will be analysed considering more traditional air interfaces based on DVB standards, mainly for the return link. Therefore, a DVB-S2X is considered for the forward link, and a DVB-RCS2+M for the return link. |
| | 11 | Inmarsat 5 (GEO / Ka-band) | Inmarsat SATCOM system that provides broadband services by means of Ka-band high-throughput satellites (HTS). Currently there are 3 GEO satellites providing service worldwide, and another one is under development to increase capacity. Air interface will be based on DVB family, in particular on TDM/MF-TDMA for the forward and return link, respectively. |

Table 28: List of SATCOM solutions to be analysed

# 9. SATCOM SOLUTIONS ASSESSMENT

The assessment of the SATCOM solutions proposed in section §6 is mainly **qualitative**, although complementary quantitative analyses have also been performed for the justification of some criteria. The objective is to evaluate each criterion for each SATCOM solution and determine if they are Compliant (C), Partially Compliant (PC), Non-Compliant (NC) or Not Applicable (N/A). A justification or explanation is also provided in order to clarify and justify the assessment. Bearing in mind that the main part of the assessment is qualitative, it has been considered important to add **extra granularity** on the *compliant* evaluation of the technical and multi-technology criteria. This way, it is easier to differentiate the systems that clearly comply with a particular criterion from other ones that could comply (and in fact are marked as a compliant) but present more difficulties or are conditioned to other factors. Thus, the evaluation is more accurate and facilitates the process of drawing conclusions.

Therefore, Table 29 summarises possible evaluation results used in the assessment.

| Value | | Meaning |
|---|---|---|
| C | C (High) | Compliant (*High*) |
| | C | Compliant (*Normal*) |
| | C (Low) | Compliant (*Low*) |
| PC | | Partially Compliant |
| NC | | Non-Compliant |
| N/A | | Not Applicable |
| Unk | | Unknown |

Table 29: Values for the technical criteria evaluation

## 9.1 TECHNICAL AND FUNCTIONAL ASSESSMENT

The evaluation of the technical and functional criteria is performed considering the 2-dimensions of the compliance matrix:

- On one hand, it is evaluated the compliance of each criterion regarding the different SATCOM proposed solutions (*i.e.* horizontal assessment).
- And, on the other hand, it is also taken into account the assessment of each SATCOM solution regarding all technical criteria (*i.e.* vertical assessment).

The assessment of each criterion per each SATCOM solution is explained in detail in Annex §C. And the 2 different points of view (horizontal and vertical assessments) are explained into more detail in the following subsections.

### 9.1.1 Horizontal assessment of technical and functional criteria

Table 30 shows the assessment of each technical criterion regarding the proposed SATCOM solutions (*i.e.* the horizontal assessment).

| Criterion ID | Related parameter | Conclusion |
|---|---|---|
| CRT-TECH-1 | *Link availability* | Link availability is one of the **most demanding requirements derived from critical railway applications**. Although it is very complicated to find a good compromise between achieving high availability and enabling SOTM terminals and/or handhelds, it is important to remark that it takes advantage of the very low data rates of the applications.<br>**Lower constellations (*i.e.* LEO, MEO) and Lower frequency bands (*i.e.* L, S C) offers more favourable conditions** than GEO constellation and higher frequency band (*i.e.* Ku , Ka - band) where worse weather conditions have to be supported |
| CRT-TECH-2 | *Reliability* | The end-to-end QoS requirements of a communication call/session shall be guaranteed according to user's SLA. **It is reached for all of the solutions proposed** since backup and/or redundancy (*i.e.* duplication) for these critical elements can be assumed in the most of the cases in order to reach the MTBF and MTTR figures. |
| CRT-TECH-3 | *Error ratio* | **It is reached for all of the solutions proposed** since several mechanisms are nowadays provided for commercial communication standards (*e.g.* DVB-S2/X/RCS2, etc.) to guarantee a high level of service continuity. Most of these techniques are implemented at L1 and L2 layers (*e.g.* FEC, LL-FEC, ARQ, etc) |
| CRT-TECH-4 | *Transfer delay* | **Latency requirement is other one of the most demanding requirements for safety applications**. It is observed that GEO systems are a priori discarded since the double-hop required for terminal-to-terminal communications (in star topologies) and larger distance to the earth supposes more than 0.5s. **SATCOM transmission delay can be similar to the one provided by terrestrial systems only using non-GEO orbits** (*i.e.* LEO or MEO). GEO satellites transmission delay could be accepted or not according to final applications requirements. |
| CRT-TECH-5 | *Delay jitter* | There exist mechanisms at IP level able to compensate the delay time variations between packets. Such **closed solutions** (*i.e.* iridium, Inmarsat, Thuraya), which **offer voice services with Circuit Switched**, **are not providing relevant differences in the quality of the voice services**. |
| CRT-TECH-6 | *Network registr. delay* | It depends on the network synchronisation mechanism implemented by each particular solution. The **systems requiring localization information are not meeting the requirements** since cold acquisition time for GNSS systems are long (*e.g.* Inmarsat…). **ANTARES CS was designed in order to not require external systems** for assuring the operational requirements. |
| CRT-TECH-7 | *Call establ. delay* | The proposed **closed systems (*i.e.* Iridium, Inmarsat, Thuraya), which are using Circuit Switched for providing voice calls, are non-compliant**. Use of pure **RA** (*e.g.* ANTARES, S-MIM, Smart LNB) **is taking advantage of asynchronous access** in order to minimise time delay for accessing to the network. Other proposed solutions based on IP and DAMA access schemes can meet the requirement with an appropriate sizing of the network resources. |

| *Criterion ID* | *Related parameter* | *Conclusion* |
|---|---|---|
| CRT-TECH-8 | *Capacity* | **Higher frequency bands** (*e.g.* X, Ku and Ka) **can provide more capacity than lower frequency bands** (*e.g.* L, S, C) where **spectrum resources are much more limited**. |
| CRT-TECH-9 | *Priority and pre-emption* | This requirement is **very important in environments where heterogeneous services have to be supported** (different QoS requirements per application). It can be satisfied for all the proposed solutions since it can be implemented at IP (L3) through QoS IP routers independent of the selected bearer. |
| CRT-TECH-10 | *Types of services* | **Solutions all IP based are going to support voice and data independently**, since it is only addressed as two different services with different QoS requirements. For these proposed systems enabling the use of handhelds, it is worth highlighting that voice services are currently offered through Circuit Switched network. |
| CRT-TECH-11 | *Bandwidth* | **The higher the frequency band** operated by a SATCOM system, **the higher the number of applications supported** (*i.e.* more bandwidth/data rate available). In this sense, systems operating at **low frequency bands (narrowband) are capable to provide capacity to ETCS data and voice services** whilst SATCOM systems operating at high frequency bands (mainly Ku and Ka) can also provide broadband services, such as internet for passengers. |
| CRT-TECH-12 | *Types of comms* | **Proposed solutions based on All IP services are going to meet with these requirements since IP level solution can be implemented independently of the selected bearer**. However, it is very important to highlight that currently deployed systems are not oriented to offer user to multi-user communications from remote terminal point of view. Although probably most of them can do it with some little modifications in the management plane. |
| CRT-TECH-13 | *Coverage* | **There are no issues for the proposed solutions to provide European coverage to the railway network.** For example, O3b was discarded during the filtering performed at the beginning of task 3 due to mainly its purpose, more focused on providing backhaul services than SATCOM on the move. Some of the proposed systems are providing worldwide coverage like Inmarsat and Iridium |
| CRT-TECH-14 | *Mobility* | **The majority of the proposed solutions are going to meet this requirement; however, some of them shall implement additional mechanisms** (*e.g.* doppler compensation mechanism) **to enlarge the range of supported errors** required to higher speeds up to 500 Km/h). Commercial standards like DVB-RCS are including specific annex for mobile environments, referred as DVB-RCS+M. |

| Criterion ID | Related parameter | Conclusion |
|---|---|---|
| CRT-TECH-15 | *Flexibility* | It refers to the configurability of the system regarding channelization modes (signal bandwidth, SF, etc.), set of modcods available (code rates and modulations), etc. **Commercial standards like DVB-S2 and RCS2 are designed to provide high flexibility**. However, constrains from the other system elements (*e.g.* terminal constrains, Satcom EIRP and G/T, etc) can limit flexibility and show differences among these solutions using the same air interface. |
| CRT-TECH-16 | *Scalability* | It refers to the spectral bandwidth availability for future extensions of the capacity in term of users or new applications more demanding on data rate. **Solutions operating at higher frequency bands are going to provide more scalability than these ones operating at lower bands where the spectrum resources are more limited**. In addition, commercial satellites can be more scalable since there exist more operators offering transponders in the same bandwidth like are the case of C, Ku and Ka band. |
| CRT-TECH-17 | *Types of terminals* | **The most restrictive type of terminal in terms of size, weight and power (SWaP) is the handheld. Only low frequency bands are able to provide all types of terminals** required by the railway domain (including handhelds). SATCOM systems providing handhelds (*e.g.* Iridium, Inmarsat...) are not taking into account the required link availability demanded by safety critical applications, since they were conceived for commercial voice calls. Solutions enabling handhelds are providing voice services based on Circuit Switched. **High frequency band solutions do not provide handhelds**. In addition, fixed and on-board terminals are more complex and expensive, since directional and steerable antennas shall be used. |
| CRT-TECH-18 | *Safety* | It refers to the robustness of the bearer to non-intentional RF interferences. In principle, **the majority of the solutions are providing several techniques to counteract the impact of the RF interference** or also mitigate the fading, in order to keep high values of link availability. Example of these techniques are, ACM, UPC, Diversity techniques, Spreading, Channel Interleavings, etc. |
| CRT-TECH-19 | *Security* | **Commercial SATCOM solutions generally do not provide mechanisms to prevent intentional attacks and/or counteract intentional RF interferences (*i.e.* jammings) at bearer level.** However, **Inmarsat BGAN provides authentication and encryption at L2** since this service is used in the aeronautical domain for air traffic control applications and related ones.<br><br>On the other hand, everyday more and more baseband technologies (e.g. iDirect, Comtech, etc) are including new functionalities at L1/L2 layers of their products oriented to offer protected waveforms, *i.e.* TRANSEC/COMSEC (e.g. AES-256 and FIPS encryption algorithms, etc). However, any of these techniques is still included in the commercial communication standards.<br><br>It is worth noting that most of the security functionalities can be implemented at IP (L3) or upper layers, which fall out of the scope of this assessment. |

Table 30: Horizontal assessment of technical and functional criteria

### 9.1.2 Vertical assessment of technical and functional criteria

Table 31 shows a brief assessment of each SATCOM solution regarding all technical criteria (*i.e.* the vertical assessment).

| *1 – Iridium NEXT* | *2 – MEO / C-band* |
|---|---|
| ▪ Strengths:<br>▪ Delay<br>▪ Simple on-board terminals<br>▪ Handhelds<br>▪ Weaknesses:<br>▪ Availability for railway safety apps<br>▪ Capacity<br>▪ Handhelds support only circuit-switched | ▪ Strengths:<br>▪ Delay<br>▪ Simple on-board terminals<br>▪ Handhelds<br>▪ Availability for railway safety apps<br>▪ Weaknesses:<br>▪ Theoretical system (not planned to be implemented) |
| *3 – Inmarsat 4 and 6* | *4 – GEO / L-band + ANTARES (IRIS FOC)* |
| ▪ Strengths:<br>▪ Simple on-board terminals<br>▪ Handhelds<br>▪ Security (authentication and encryption level 2)<br>▪ Weaknesses:<br>▪ Delay (mainly between SATCOM users)<br>▪ Availability for railway safety apps<br>▪ Handhelds support only circuit-switched<br>▪ Network registration delay (depends on GPS positioning system) | ▪ Strengths:<br>▪ Simple on-board terminals<br>▪ Handhelds<br>▪ Weaknesses:<br>▪ Delay (mainly between SATCOM users)<br>▪ Limited number of voice connections (oriented to data apps)<br>▪ Implementation planned from 2025 under ESA IRIS program |
| *5 – Thuraya* | *6 – GEO / S-band (S-MIM)* |
| ▪ Strengths:<br>▪ Simple on-board terminals<br>▪ Handhelds<br>▪ Weaknesses:<br>▪ Availability for railway safety apps<br>▪ Delay (mainly between SATCOM users)<br>▪ Capacity<br>▪ Handhelds support only circuit-switched<br>▪ High-speed mobility | ▪ Strengths:<br>▪ Simple on-board terminals<br>▪ Handhelds<br>▪ Weaknesses:<br>▪ Delay<br>▪ Aimed at data applications (limited number of voice connections simultaneously) |

| *7 – GEO / C-band* | *8 – GEO / X-band (GovSat)* |
|---|---|
| ▪ Strengths:<br>  ▪ Simple on-board terminals<br>  ▪ Availability for railway safety apps<br>▪ Weaknesses:<br>  ▪ Delay (mainly between SATCOM users)<br>  ▪ Handhelds not supported | ▪ Similar to GEO / C-band system, but with a worst link availability |
| *9 – SmartLNB* | *10 – GEO / Ku-band* |
| ▪ Weaknesses:<br>  ▪ Complex on-board terminal<br>  ▪ Handheld not supported<br>  ▪ Availability for railway safety apps<br>  ▪ Delay<br>  ▪ Oriented to data applications (limited number of voice connections simultaneously (if supported)) | ▪ Strengths:<br>  ▪ Broadband system capable of providing additional services<br>▪ Weaknesses:<br>  ▪ Complex on-board terminal<br>  ▪ Handheld not supported<br>  ▪ Availability for railway safety apps<br>  ▪ Delay (mainly between SATCOM users) |
| *11 – Inmarsat 5 / GEO/Ka-band* | |
| ▪ Strengths:<br>  ▪ Broadband system capable of providing additional services<br>▪ Weaknesses:<br>  ▪ Complex on-board terminal<br>  ▪ Handheld not supported<br>  ▪ Availability for railway safety applications<br>  ▪ Network registration delay (depending on GPS positioning)<br>  ▪ Delay (mainly between SATCOM users) | |

Table 31: Vertical assessment of technical and functional criteria

### 9.1.3 Compliance matrix of the technical and functional criteria

Figure 68 shows the compliance matrix of the technical and functional criteria.

| Criterion ID | Satcom technology | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| | Iridium NEXT | MEO / C-band | Inmarsat 4 (BGAN) - Inmarsat 6 (ICE) | IRIS FOC | Thuraya | GEO / S-band | GEO / C-band | GEO / X-band | SmartLNB | GEO / Ku-band | Inmarsat 5 (Global Xpress) |
| CRT-TECH-1 | NC | C | NC | C (Low) | NC | C (Low) | C (Low) | NC | NC | NC | NC |
| CRT-TECH-2 | C (Low) | C (High) | C (Low) | C (High) | C (Low) | C (Low) | C (High) | C (High) | C (High) | C (High) | C (High) |
| CRT-TECH-3 | C | C | C | C | C | C | C | C | C | C | C |
| CRT-TECH-4a | C (High) | C (High) | NC | C (Low) | C (Low) | NC | C (Low) | C (Low) | NC | C (Low) | C (Low) |
| CRT-TECH-4b | C (High) | C (High) | NC | NC | NC | NC | NC | NC | NC | NC | NC |
| CRT-TECH-5 | C (High) | C (High) | C (Low) | C (Low) | C (Low) | C (Low) | C (Low) | C (Low) | C (Low) | C (Low) | C (Low) |
| CRT-TECH-6 | C | C | NC | C | C | C | C | C | C | C | NC |
| CRT-TECH-7 | NC | C | NC | C (High) | NC | C (High) | C | C | C (High) | C | C |
| CRT-TECH-8 | NC | C | PC | C | NC | C | C | C | C | C | C |
| CRT-TECH-9 | C | C | C | C | C | C | C | C | C | C | C |
| CRT-TECH-10 | C | C | C | C (Low) | C | PC | C | C | PC | C | C |
| CRT-TECH-11 | C | C | C | C (Low) | C (Low) | C (Low) | C | C | C | C (High) | C (High) |
| CRT-TECH-12 | NC | C | NC | C | NC | C | C | C | C | C | NC |
| CRT-TECH-13 | C | C | C | C | C | C | C | C | C | C | C |
| CRT-TECH-14 | C | C | C | C | NC | C | C | C | PC | C | C |
| CRT-TECH-15 | C (Low) | C (High) | C | C (Low) | C (Low) | C (Low) | C (High) | C (High) | C (Low) | C (High) | C (High) |
| CRT-TECH-16 | C (Low) | C (Low) | C (Low) | C (Low) | NC | C (Low) | C (High) | C | C (High) | C (High) | C (Low) |
| CRT-TECH-17 | C (Low) | C | C (Low) | PC | C (Low) | C | PC | PC | PC | PC | PC |
| CRT-TECH-18 | C (Low) | C (High) | C (High) | C (High) | C (Low) | C (High) | C (High) | C (High) | C (High) | C (High) | C (High) |
| CRT-TECH-19 | NC | NC | C | NC | NC | PC | NC | NC | PC | NC | NC |

Figure 68: Compliance matrix of technical and functional criteria

## 9.2 MULTI-TECHNOLOGY ASSESSMENT

Table 14 shows the multi-technology criteria identified in the first task of this study. They refer to those aspects related with the existence of more than one communications systems (satellite and/or terrestrial) that has to be analysed and solved before starting their operation in order to provide the QoS expected (which is of high relevance since these criteria apply to a complete communications architecture that shall support, among others, critical applications).

Criteria defined in Table 14 can be divided in two main groups:

| | | |
|---|---|---|
| 1 | Criteria that apply to every communications system of the FRMCS (*i.e.* can be evaluated separately to each communications system). | CRT-MULT-1 |
| 2 | And criteria required for the correct integration of the different communications systems belonging to the FRMCS. | CRT-MULT-2<br>CRT-MULT-3<br>CRT-MULT-4 |

Table 32: Multi-technology criteria division

The first group of multi-technology criteria defined in Table 32 can (and shall) be evaluated for all the Satcom solutions. But the second group of criteria do not depend on the Satcom (or terrestrial) system(s), but on final solution/implementation regarding how the different systems of the full architecture are going to coexist.

Therefore, only criteria belonging to the first group of multi-technology criteria can (and shall) be assessed for each Satcom solution. For the rest of multi-technology criteria, particular comments and a justification regarding mechanisms and/or elements that are related with them are provided in following sections.

### 9.2.1 Assessment of multi-technology criteria

Table 33 shows the evaluation of the criteria belonging to the first group of multi-technology criteria (see Table 32), which apply to every communications system being part of the future railway mobile communications architecture. In this case, only **CRT-MULT-1** criterion is evaluated.

| ***CRT-MULT-1:*** *All communication networks (e.g. SATCOM and terrestrial) of the future railway communications architecture shall be packet-switched (PS), since all the applications supported shall be IP based.* | | | |
|---|---|---|---|
| ***Satcom Solution*** | | ***Evaluation*** | ***Justification*** |
| *1* | *Iridium NEXT* | C (Low) | Iridium NEXT keeps Circuit Switched system in order to be backward compatible with former Iridium terminals. It also adds a Packet Switched network supporting IP based services. It is marked as "C (Low)" because natural way to provide voice communications is by means of its Circuit Switched part of the system. |
| *2* | *MEO / C-band* | **C (High)** | As a future network, it will be designed according to NGN concept, *i.e.* based on IP services. |
| *3* | *Inmarsat 4 (BGAN) - Inmarsat 6 (ICE)* | C (Low) | I4 (BGAN) is a blend of Circuit Switched and Packet Switched system. Although voice calls are currently served by the Circuit Switched system, it supports VoIP and videoconferencing services via the Packet Switched system.<br>I6 is expected to strengthen the Packet Switched and IP-based services. |
| *4* | *GEO / L-band + ANTARES CS (IRIS FOC)* | C | As a future network, it will be a Packet Switched system supporting IP-based services. It is graded as "C" because although it can offer IP services (data and voice apps), only a few number of voice connections could be provided simultaneously (lots of simultaneous voice connections decrease efficiency in a pure random system). |
| *5* | *Thuraya* | C (Low) | Thuraya is mainly circuit-switched oriented, being compatible with GSM system. In addition, it includes a packet-switched technology compatible with GPRS, being able to provide IP data, as well. It is graded as "C (Low)" because although it can offer IP services, voice applications are best offered by the non-IP part of the system. |
| *6* | *GEO / S-band* | C | GEO / S-band solutions based on Packet Switched systems supporting IP-based services are considered.  It is graded as "C" because although it can offer IP services, it is not conceived for voice services (only a very few number of voice connections could be provided simultaneously. Otherwise, system efficiency is decreased). |
| *7* | *GEO / C-band* | **C (High)** | GEO / C-band solutions based on Packet Switched systems supporting IP-based services are considered. |
| *8* | *GEO / X-band* | **C (High)** | GEO / X-band solutions based on Packet Switched systems supporting IP-based services are considered. |
| *9* | *SmartLNB* | C | SmartLNB is a Packet Switched system that supports IP-based services. It is graded as "C" because although it can offer IP services, it is not conceived for voice services (only a very few number of voice connections could be provided simultaneously; otherwise system efficiency is decreased). |

| | | | |
|---|---|---|---|
| *10* | *GEO / Ku-band* | C (High) | Only GEO / Ku-band solutions based on Packet Switched systems supporting IP-based services are considered. |
| *11* | *Inmarsat 5 (Global Xpress)* | C (High) | I5 (GX) is a Packet Switched system and supports IP-based services. |

Table 33: Assessment of multi-technology criteria for SATCOM solutions

### 9.2.2 Compliance matrix of the multi-technology criteria

Thus, the compliance matrix for the multi-technology criteria is directly filled in from Table 33 (see Figure 69).

| Criterion ID | Satcom technology | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| | Iridium NEXT | MEO / C-band | Inmarsat 4 (BGAN) - Inmarsat 6 (ICE) | IRIS FOC | Thuraya | GEO / S-band | GEO / C-band | GEO / X-band | SmartLNB | GEO / Ku-band | Inmarsat 5 (Global Xpress) |
| CRT-MULT-1 | C (Low) | C (High) | C (Low) | C | C (Low) | C | C (High) | C (High) | C | C (High) | C (High) |

Figure 69: Compliance matrix of the multi-technology criteria

### 9.2.3 Multi-technology criteria not evaluated

Table 34 shows particular comments and a justification regarding mechanisms and/or elements that are related with the second group of multi-technology criteria (see Table 32), which do not apply directly to each communications system belonging to the final communications architecture, but to the mechanisms used for the correct integration of these systems.

| *Criterion ID* | *Criterion* | *Comments* |
|---|---|---|
| CRT-MULT-2 | *The end-to-end QoS of a communication call/session shall be guaranteed according to user's SLA.* | One of the main Next Generation Network (NGN) feature is the separation between service and transport layers. It allows the service layer to reserve the required resources for every user information exchange (voice and/or data) independently of the bearer before starting the transaction. And these resources are kept (and adapted if required) until the end of the communication.<br>This requirement relies directly to the mechanism to be adopted/implemented to assure the end-to-end QoS independently of the number of bearers used. For multimedia sessions, a possible solution could be based on IMS (*IP Multimedia Subsystem*), which is also the solution adopted by LTE (Long Term Evolution). |
| CRT-MULT-3 | *Handovers among systems (also known as vertical handovers) shall be transparent to users (i.e. seamless).* | The FRMCS can consist of several communications systems (bearers). Users can use these bearers according to their own configuration and their current coverage.<br>The mechanism/equipment that allows a smooth transition between bearers without disrupting the service when required is very important in a multi-technology environment, but it does not depend on the Satcom system because it is a transversal solution to all the systems belonging to the final architecture. Therefore, this criterion cannot be assessed against Satcom solutions, but to the final communications architecture. |

| Criterion ID | Criterion | Comments |
|---|---|---|
| CRT-MULT-4 | *FRMCS user terminals shall be able to provide communications taking into account a multi-technology communication architecture.* | Railway environment requires several types of terminals. Taking into account that several bearers can coexist, it is required that (at least some of these) terminals can provide service by means of several bearers (in order to avoid having one different terminal per technology).<br>Therefore, this criterion shall be evaluated against the implementation of future terminals providing service by different bearers. |

Table 34: Multi-technology criteria not evaluated

## 9.3 NON-TECHNICAL AND NON-FUNCTIONAL ASSESSMENT

### 9.3.1 Cost Benefit Analysis scope and main assumptions

This section is devoted to introducing and detailing the scope and the main assumptions of the analysis. It includes a definition of the time horizon and the geographic scope; a definition of the scenarios assessed, a listing of the stakeholders involved, and a list of the main assumptions used, along with the essential data that feeds the analysis.

#### 9.3.1.1 Key Inputs and Preceding Studies

This analysis exploits the results of a series of previous studies performed by the European Commission and the European Union Agency for Railways to consistently feed and forecast the costs of the different technologies assessed. Those studies included CBA and economic analyses of the existing and new alternatives that will play a relevant role in the future communication sector. The consortium has taken those reports as key information sources to generate the cost model and to keep updating the current predictions.

The main reports consulted are the following:

- Study on the migration of railway radio communication system from GSM-R to other solutions. European Union Agency for Railways study performed by **SYSTRA.**
- Study on the use of commercial mobile networks and equipment for "mission-critical" high-speed broadband communications in specific sectors. **EC** study performed by **SCF Associates Ltd.**
- CELTIC / CP7-011 CAPEX and OPEX Evaluation Results. **MEVICO** study performed by **CELTIC**.
- ESA Study: ***Satcom4rail***, performed by **Indra** in consortium with INECO.
- Outputs from tasks *1*, *2* and *3* of this project, performed by **Indra** and **ALG**.
- **EUROSTAT** database and **railway undertaking's published information**.

#### 9.3.1.2 Time Horizon

The GSM-R system is estimated to reach obsolescence by 2030. The CBA considers that the replacement technology should be operative before 2030 and remain active at least 10 years after GSM-R. Thus, the timeline is defined as the period **2020-2040**.

#### 9.3.1.3 Geographic Scope

The geographic scope of the analysis covers the member states of the EU28, as well as Norway and Switzerland, in line with previous economic and business assessments addressing communications in the European Railway sector (seen in the above section §9.3.1.1), in order to ensure full traceability and comparability.

#### 9.3.1.4 SATCOM Costs and Infrastructure Scope

The analysis is designed to assess the feasibility of off-the-shelf SATCOM solutions, or alternative proposed solutions that have been assumed to be potentially deployable (as is the case of MEO C-band).

- Hence, the analysis does not take into account any space segment or ground mission management infrastructure, as well as any other ground infrastructure supporting the SATCOM services. These costs are treated as sunk costs, which would have been incurred out of the scope of the CBA by the time the specific railway communications capability would be deployed.
- In contrast, the SATCOM costs and infrastructure scope take into account the railway communications-specific infrastructure and assets to be deployed by the concerned stakeholders in order to provide such a GSM-R-succeeding service. Such scope is explained in more detail in section §9.3.2.1.

#### 9.3.1.5 Stakeholders Involved

Two groups of stakeholders have been identified as the main players in the rail sector:

- **Railway Undertakings,** responsible for the maintenance and operations of the transport vehicles. These operators must ensure safety and service quality, naturally interested in customer value-added services, such as Wi-Fi connection in the railway cars, as an additional revenue stream and as a passenger engagement mechanism.
- **Infrastructure Managers,** responsible for the maintenance and operations of the infrastructure where the railway undertakings are performing their commercial activities. These operators must ensure safety and quality of the infrastructures such as the rail lines, train stations, beacons, signs, to name a few. These stakeholders are interested in the positioning, monitoring, and safety services.

#### 9.3.1.6 Basic Assumptions

The basic assumptions used in the analysis are the following:

***Stakeholders***

- The materialisation of such new communications service deployment will necessarily imply the collaboration of several stakeholders in several fields and with different capabilities. However, for this study, only **two main** direct **stakeholders** involved with the service provision have been considered.
- Communications provision costs are covered, by the Infrastructure Manager, who deals directly with the communications providers. These costs are then partially recovered through the regulated service fees that Infrastructure Managers charge to Railway Undertakings. However, in this cost assessment, this transaction has not been modelled, since it is a two-way transaction between the two stakeholders characterised in the analysis, and does therefore not contribute any impact on net present value. Instead, a non-financial “ultimate economic footprint” has been computed, through this very net present value indicator, whereby Railway Undertakings are modelled as incurring the full communications costs that they are responsible for.

***Finance***

- **Macro-economic parameters** such as, inflation, population growth, demand, among others, **have not been taken into account**. The objective of this study is to determine the feasibility of the different technologies and considering a frozen growth financial scenario provides sufficient criteria to determine which technologies have more potential and their feasibility. Furthermore, SATCOM results are presented relative to terrestrial results; therefore, macro-economics will have a small impact on the final solution.
- The EU recommends the use of a **4% discount rate** related to cohesion and development projects. Thus, this discount rate has been assumed for each stakeholder.
- Investments with a lifecycle shorter than the total time horizon for the analysis are automatically renewed, generating new CAPEX. However, a buffer of 5 years has been taken into account in order to avoid reinvestments in the last years, therefore accounting for a realistic degree of lifecycle elasticity.
- **Interest and amortization** rates are **not taken into account** in this study, since financial and macro-economic analyses have been considered to fall beyond the scope of the study, as is frequent best practice in such pre-feasibility assessments.

***Technology***

- **GSM-R** will reach obsolescence by **2030** and a substitute technology is required to provide a continued service that ensures critical safety applications.
- **LTE** can be deployed in both broadband and narrowband forms within a frequency range from 400 MHz (for a minimum frequency and very narrowband application), to 2.000 MHz (for a fully broadband implementation).
    - Additionally, LTE can support high data rates in broadband implementations, provided that the deployment of base stations is sufficiently dense on the trackside to support it even at high train speeds. In total, it has been assumed that a broadband LTE implementation may require multiplying the existing number of GSM-R base stations by a factor of up to four.
    - Given the uncertainty regarding this question, with conflicting data and lacking a irrefutable conclusion, a range of factors from one (meaning no requirement for extra ground stations over current GSM-R deployments) and four (meaning three

newly-built stations for every existing, upgraded GSM-R station) has been considered, generating an open range of possible economic outcomes.

***Methodology***

- **Maintenance and other costs** *have been sized to equal a yearly 5% of the CAPEX investment* as is frequent best practice in such pre-feasibility assessments.

***Value-added services specific assumptions***

This assumptions focus on the specific analysis for value-added services for revenue generation

- The number of passengers will grow in alignment with the population's own expected growth rate in the geographic and time scope of the analysis.
- The railway market growth has been extrapolated from 10 years past data.
- The revenues are constant regardless of the technology used to provide the service. Hence, a 'platform-independent' approach is assumed from railway undertakings, since passengers are implicitly assumed to be willing to pay for a given service regardless of the actual technological platform supporting it.
- The revenue model is based on a baseline tariff per user (as the sole source of revenue for railway undertakings).
- Infrastructure managers are not expected to benefit from the provision of added-value services within the scope of this analysis.
- Adding broadband services will not alter the railway passenger demand expectations.
- It is assumed that there are no constraints regarding channel capacity for SATCOM solutions on the space side.
- Broadband services include 20 Mbps of shared broadcast on forward link (downlink) every 100 trains, and 2Mbps on return link (uplink) data traffic per train.

### 9.3.2 Methodology of the Cost Benefit Analysis

This section describes the methodology, the models and the assumptions used to derive the costs and revenue due to the use of SATCOM for railway critical safety applications and safety communications.

#### 9.3.2.1 Approach to the Analysis

The objective of this CBA is to determine which technologies are more promising for GSMR replacement. Hence, the analysis has been aligned towards a complete European assessment and overall lifecycle cost. The analysis uses a top down approach to determine the main costs incurred to each stakeholder, and the cost model differentiates cost sources depending on their recurrence. In addition, the model also clearly differentiates between terrestrial and SATCOM solutions due to their inherent differences in architecture and cost sources.

Hence, the following concepts are defined:

- **CAPEX,** or capital expenses, are the non-recurring expenses required to develop and build the technology and systems. They are incurred for all the systems, infrastructure, terminals, and other one-time investments required prior or posterior to the initialization of the service. CAPEX are related to the size of the infrastructure required for providing the service and the eventual replacement of the systems at the end of their lifecycle.

- **OPEX,** or operational expenses, are the recurring expenses required to operate the system and provide the service. OPEX are related to the costs derived from the operations themselves, bandwidth tariffs, maintenance, personnel, etc, and have a direct relationship with the volume or demand of the service. In the proposed model, this kind of expense is computed on an hourly basis when it comes to bandwidth usage costs, and on a yearly basis when it comes to other OPEX categories.

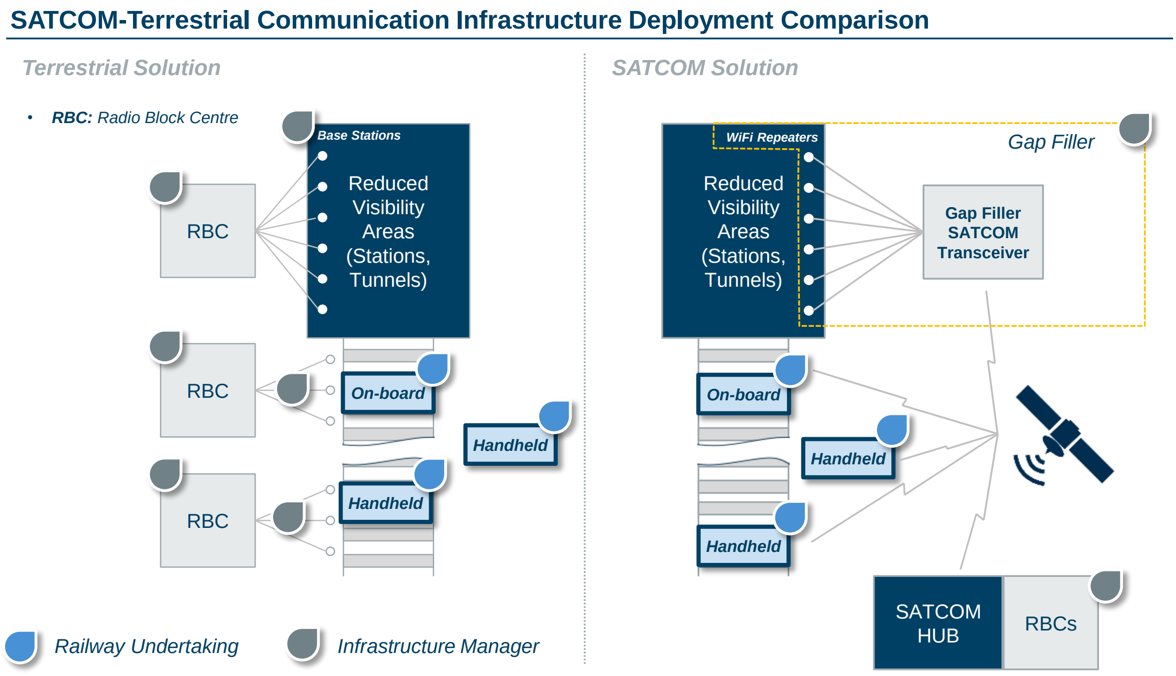



Figure 70: System architecture for terrestrial and SATCOM solutions

As seen in Figure 70, SATCOM solutions only require gap fillers for zones where the satellites have no coverage, while terrestrial solutions require base stations along all the rail lines to provide coverage of the service. Hence, the costs associated with each solution differ significantly from one another. The logical conclusion of the SATCOM architecture is that all the RBCs are located at the same place. However, this is not a realistic scenario, as currently RBCs are (or at least can be) located along the rail line and in different locations depending on the geography, technology used and infrastructure available. The RBCs will communicate with the SATCOM terminals via a dedicated line (terrestrial or even satellite) to the SATCOM HUB.

#### 9.3.2.1.1 Broadband services model approach

The analysis of broadband services has been segmented depending on the users utilising the service. Users travelling on high-speed trains are generally more willing to pay for value-added services than those travelling on short distance trains. Therefore, three different business cases have been defined:

- High speed/long distance
- Medium distance
- Short distance

Each market is modelled using the same conceptual methodology. The results will be presented as both NPVs regarding the revenue-side standalone business case and the total NPVs resulting from the technology implementation with value-added services included.

#### 9.3.2.2 Railway Undertaking

Railway undertakings are not only interested in operating the trains, but also adding value to their customers by offering new services and generating new sources of revenue. This section presents a detailed description of the parameters defined to build the model for both costs and revenue.

##### 9.3.2.2.1 Cost

Railway undertakings are in charge of the initial expense for the communication devices, both handheld and embedded. Railway undertakings are also in charge of the fees to be paid to Infrastructure Managers in partial return for the provision of communications services. In addition, they are accountable for maintaining their devices.

##### 9.3.2.2.2 Revenue

Some of the solutions evaluated include broadband offering extra value services to the end users. These additional services, such as Wi-Fi, could potentially generate a new source of revenue that could completely modify the business case of the assessed solutions. The cash flow of these value-added services will be studied in Task 4.

#### 9.3.2.3 Infrastructure Manager

Infrastructure operators do not interact directly with the end user in rail transportation. Thus, they are not interested in value-added services provided by SATCOM during the travel. As such, infrastructure managers must provide all the facilities required to enable railway undertakings to perform their activities. As a matter of fact, infrastructure managers, in their capacity as managers of railway stations, may be interested in providing value-added services to passengers within these premises. Nevertheless, these services fall beyond the scope of this study, as they are expected to be provided via other communications solutions separate from safety-critical railway communications.

Infrastructure managers are in charge of providing the required infrastructure for the service provider. Therefore, they are in charge of the initial capital expense for gap fillers and their own communication devices, both handheld and embedded. Infrastructure operators are also in charge of the operational expenses that arise from the use of the services such as maintenance costs and the communication infrastructure running costs.

In the case of terrestrial solutions, infrastructure managers are in charge of the costs associated with base stations.

#### 9.3.2.4 Cost Model

The cost model is built by segmenting each subsystem influencing the costs. The breakdown subsystem scheme for the model is shown in Figure 71.

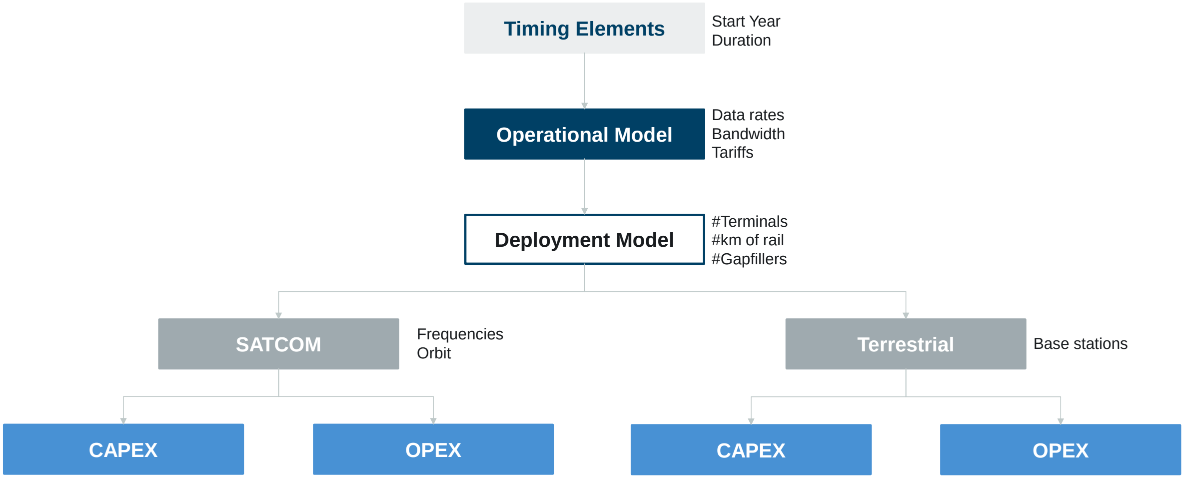



Figure 71: Cost model subsystem breakdown

##### 9.3.2.4.1 Timing Elements

The time framework defined in the model contemplates the period between 2020 and 2040. The investment and maintenance costs have been computed for the provision of the service during the whole period. As mentioned previously, operational costs are charged recurrently and will have an impact on the yearly investment requirements. On the other hand, capital expenses, by definition, are one-time investments at the beginning of the period. Nevertheless, the systems reach an end of life and they require eventual replacement. This replacement is defined by the lifecycles of the system described in the table below. There are some restrictions on CAPEX investments when the technology is close to obsolescence. Hence, no re-investment is performed after 2035.

| SATCOM | Value |
|---|---|
| **Lifecycle** | |
| Rolling Stock Operator Trainset Devices Lifecycle | 12 years |
| Rolling Stock Operator Handheld Devices Lifecycle | 12 years |
| Infrastructure Manager Gap Filler - SATCOM Side Lifecycle | 12 years |
| Infrastructure Manager SATCOM Hub Lifecycle | 12 years |

| Terrestrial | Value |
|---|---|
| **Lifecycle** | |
| Railway Undertaking Trainset Devices Lifecycle | 12 years |
| Railway Undertaking  Handheld Devices Lifecycle | 12 years |
| Infrastructure Manager Base Stations Lifecycle | 12 years |

Table 35: Lifecycle concepts defined in the model

#### 9.3.2.4.2 Operational Model

The operational model quantifies the total data rate and bandwidth used by the rail sector in Europe. It also takes into account the communication tariffs depending on each technology.

#### 9.3.2.4.3 Deployment Model

The deployment model quantifies the km of rail present in Europe, the number of terminals required, gap fillers, SATCOM hubs and base stations.

#### 9.3.2.4.4 Formulation of the model

As mentioned previously, the model is structured in terms of CAPEX and OPEX cost for each solution group (terrestrial or SATCOM). In this section, flow diagrams will be used to detail how the cost model has been built and how the costs have been modelled.

##### 9.3.2.4.4.1 CAPEX

The CAPEX costs for terrestrial and SATCOM exhibit significant similarities regarding terminal costs. Each technology has its own terminal price and investment requirements. Nevertheless, the same strategy has been applied for both solution groups. The main difference between terrestrial and SATCOM regarding CAPEX costs is that the SATCOM solution requires gap fillers while terrestrial requires base stations.

Figure 72 shows the flow diagrams for computing the CAPEX depending on the solution group.

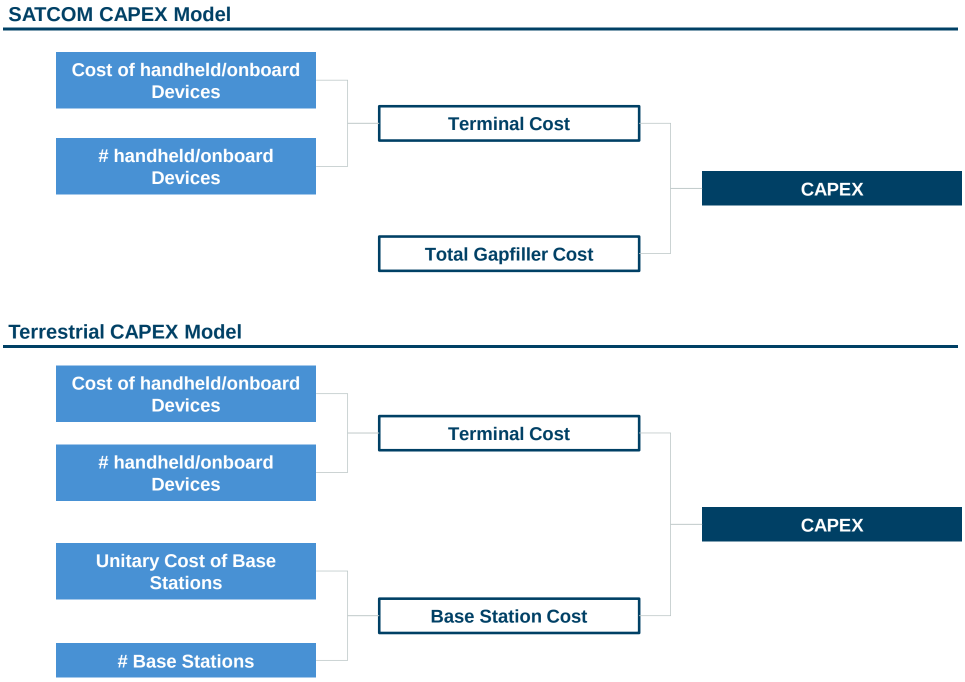



Figure 72: CAPEX flow diagram

#### 9.3.2.4.4.1.1 Gap fillers

Gap fillers must cover zones where the train has no line-of-sight with the satellites. Each gap filler is formed by a SATCOM communication terminal and Wi-Fi repeaters for terrestrial coverage. Figure 73 shows how the gap filler CAPEX cost has been modelled.

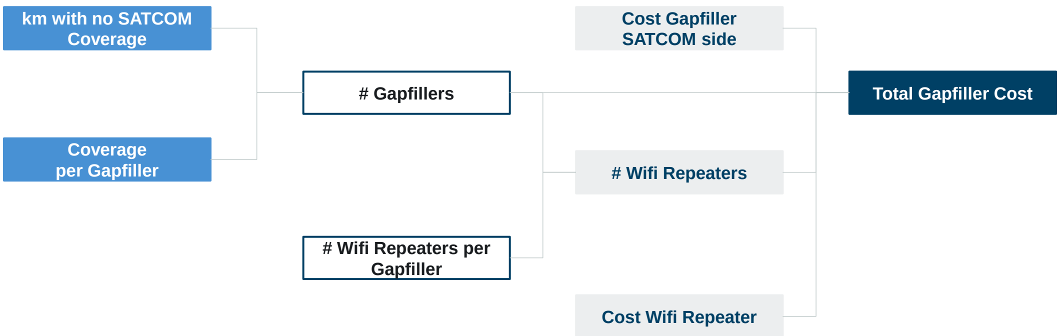



Figure 73: Gap filler flow diagram

#### 9.3.2.4.4.2 OPEX

Even though communication requirements do not depend on the technology used, there exist significant differences between terrestrial and SATCOM operational expenses due to the tariffs and infrastructure maintenance. Figure 74 shows how the operational expenses have been modelled.

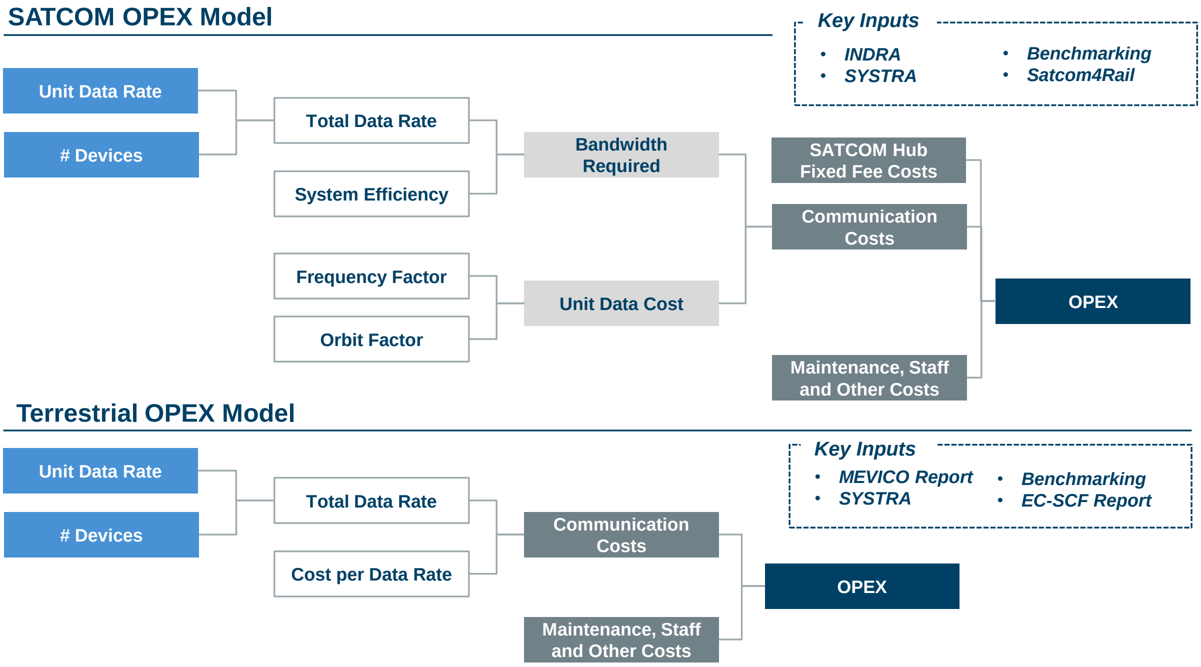



Figure 74: OPEX flow diagram

9.3.2.4.4.2.1 SATCOM Hub

SATCOM hubs are required to communicate with the RBCs which process the train traffic data and are crucial infrastructure independently of the solution. An OPEX-only model has been assumed for SATCOM Hubs, whereby a service provider would manage the hub () and sell a fee-based service via a service level agreement to the infrastructure managers, who would then provide services to railway undertakings as described elsewhere in this analysis. The conservative case of one SATCOM Hub per country (thirty states in total, including EU-28 Norway + Switzerland) has been considered. This is regarded as a conservative approach, since the general trend for most service providers is to operate lower numbers for such a region.

9.3.2.4.4.3 Ground station deployment model as a function of the operating frequency and data rate

There are some technologies, such as LTE, that can operate in a wide range of frequencies. Depending on the operating frequency and the total bandwidth available, LTE can provide narrowband or broadband solutions. The use of one frequency or another to provide the service has an important impact on the cost, mainly for infrastructure managers as the cell coverage decreases as the frequency rises. The higher the frequency, the more reduced is the coverage achievable by the system, requiring this way more ground base stations to provide the service. It is worth mentioning that the number of base stations and the number of antennas per base station will also increase with the data rate provided.

Figure 75, shows the dependency of the cell coverage capacity on the frequency and how this translates into the need for more base stations.

The cell range function can be approximated to an exponential function, however for the frequencies chosen (400-2.000 MHz) the curve can be approximated to a linear function.

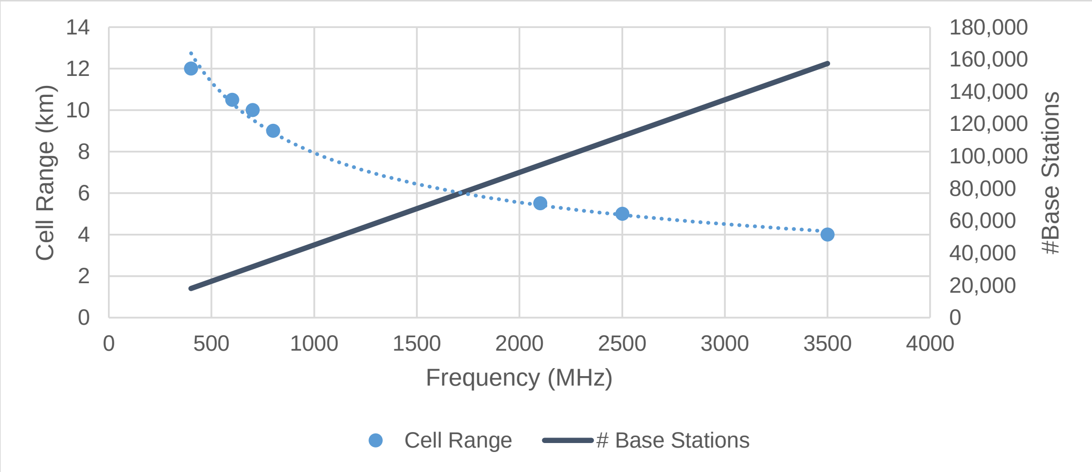



Figure 75: Cell range depending on frequency (SCF Associates-EC model)

The result, as shown in the plot above, suggests that a broadband implementation of LTE (likely in the 2000 MHz band) would require stations to be deployed every 6 km, as opposed to 8 km for a typical narrowband implementation (at 900 MHz, close to current GSM-R).

Besides this frequency-related factor, another key factor impacting base station deployments for terrestrial technologies is the data rate. This affects broadband terrestrial solutions most especially, precisely because data rates are higher. Despite multiple studies and a number of trials on this subject, findings have so far failed to point at an uncontested conclusion. It has been suggested that, while current narrowband GSM-R base stations could be upgraded to provide broadband LTE services, the need to guarantee a higher data rate would require anywhere from twice to four times the number of stations operating at a given frequency in order to reduce the effective distance between them.

As a consequence, a broadband implementation of LTE could ultimately require base stations to be deployed every 2 km compared to the 8 km typically used for GSM-R, resulting in a four-fold increase in their overall number. In practice, this would require an upgrade of all existing GSM-R stations to become LTE-compliant (albeit maintaining their installations and power lines), and the all-new deployment of the remaining 75%.

This factor, however, may be regarded as a conservative worst-case scenario. Hence, the study has considered an open factor ranging anywhere from one (where no extra deployment would be required) to four (where this most conservative assumption would become a reality). This open factor is one of the key sensitivities of the study, as discussed in further sections.

#### 9.3.2.4.5 Formulation of the Model for Value-added Services

In this subsection, the methodology to build the model for broadband services is presented. It contemplates both the revenues and the cost originated by the value-added services.

#### 9.3.2.4.5.1 Revenues

The main source of revenue is the Wi-Fi tariff that the final user will pay for accessing the internet or broadband services. It must be noted that this study only contemplates one of the multiple sources of revenue and, therefore, the results obtained are conservative. A detailed conceptual breakdown of how the revenues are computed is described below.

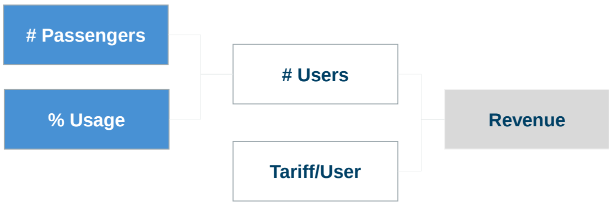



Figure 76: Value-added services Revenues breakdown model

The number of passengers has been estimated through population statistics and passenger travels (according to EUROSTAT). The coefficient between these indicates the railway usage among the population. This coefficient has been extrapolated from the last 10 years of historical data, and has been multiplied by the estimated population growth to determine the future railway demand. Figure 77 shows the expected railway passenger travel in Europe between 2020 and 2040.

Thereafter, the market has been split into high speed, medium distance and short distance trains. Following that division, a usage factor has been defined, a parameter indicating the travellers' willingness to pay for the service in each market. Finally, from the demand, and the willingness to pay for the service, the number of users is calculated. Through multiplying this figure by the service's tariff, the total revenue is obtained.

| **Share** | |
|---|---|
| High Speed | 5% |
| Medium Distance | 15% |
| Short Distance | 80% |
| **Usage** | |
| High Speed | 35% |
| Medium Distance | 20% |
| Short Distance | 10% |
| **WIFI Tariffs** | |
| High Speed | 4.0 €/user |
| Medium Distance | 2.0 €/user |
| Short Distance | 1.5 €/user |

Table 36: Input for revenue model

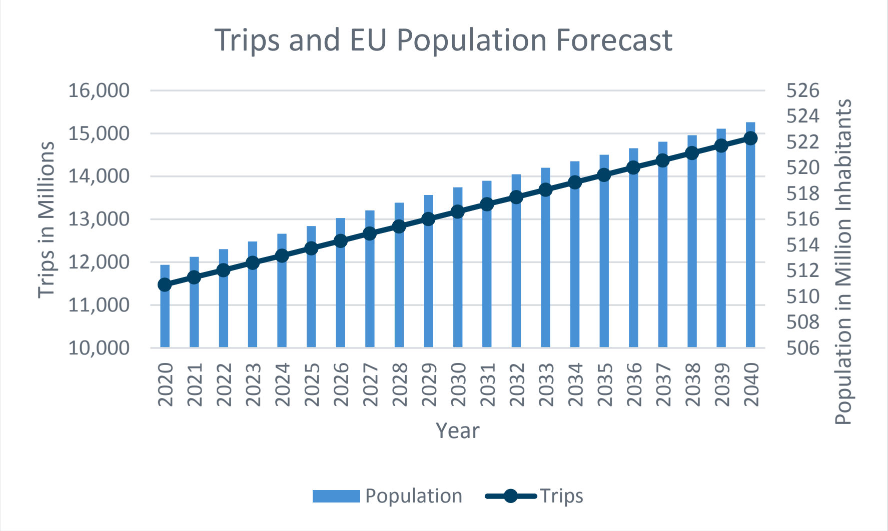



Figure 77: Railway number of trips and population forecast

#### 9.3.2.4.5.2 Cost

Adding broadband services is not free of charge for the railway undertaking, since additional equipment is required compared to just safety-critical functional applications, in particular the Wi-Fi repeaters in passenger cars or, for LTE, the land infrastructure enhancement, which affects the infrastructure manager. Hence, some investment is required from these stakeholders. In this subsection it is assessed how the capital and operational expenses related to the value-added services have been modelled.

Figure 78 shows the CAPEX investment required to enable the service.

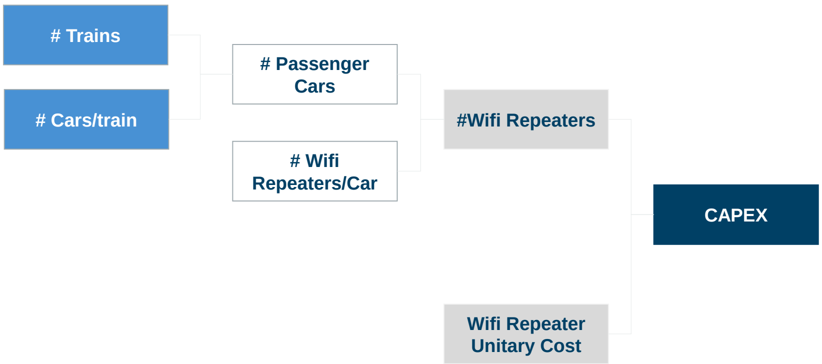



Figure 78: Value-added services CAPEX breakdown model

Regarding OPEX, offering broadband services implies a significant rise on the data rates and bandwidth allocation. Hence, the communication expenses increase accordingly. As a result, the operational expenses experience a multiplying effect compared to the original baseline. The figure below shows the conceptual breakdown modelled to compute the OPEX originated by the value-added services.

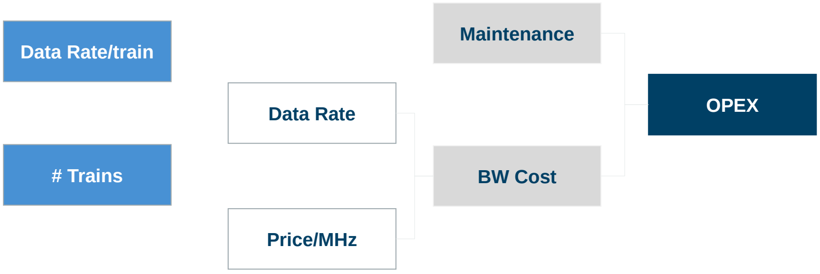



Figure 79: Value-added services OPEX breakdown model

In addition to the model above, in the case of LTE, a 50% extra cost for enhancing the base station equipment is allowed for in order to enable broadband services, and this has an impact on both CAPEX and OPEX. This enhancing cost is completely incurred by the Infrastructure Manager.

### 9.3.3 Results Analysis and Recommendations

This section is devoted to presenting the quantitative cost for each stakeholder for the scenarios analysed.

#### 9.3.3.1 Approach to the analysis

The objective of this feasibility study is to determine which alternative is more suitable for GSM-R replacement. Thus, the costs and investment requirements of each option evaluated will be presented relative to GSM-R. Notwithstanding, the model supports the use of any technology as a baseline for comparison. Broadband services results will be presented as absolute values.

#### 9.3.3.2 Preliminary Results

The market is clearly divided among narrowband solutions, which are ideally suited to the needs of safety-critical functional requirements; and broadband solutions, which require a larger investment, but have the potential to generate a return through value-added services.

This distinction is clearly shown in Figure 80, where, in narrowband, all technologies apart from TETRA present positive net present values when compared to GSM-family solutions (including GSM-R or GPRS, with equally modelled cost structures). On the other hand, broadband solutions showcase higher net present values due to the generation of revenues thanks to the scope for value added services. As mentioned before, LTE has been considered an option in both categories due to its broad range of applicability. A narrowband implementation has been considered at a typical 900 MHz (a medium value in the region of used for GSM-R or GPRS), while a broadband implementation has been proposed in the 2.000 MHz band.

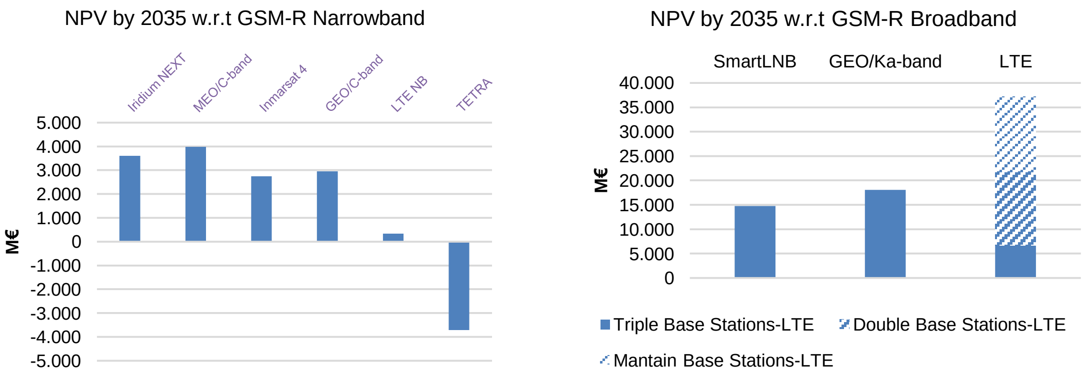



Figure 80: Net Present Value by 2035, relative to GSM-R, of the different narrowband (left) and broadband (right) solutions.

Specifically, in the case of a broadband LTE implementation, a range of possible NPV values are shown. This is due to the high uncertainty in the ultimate requirement for base station deployment necessary to support broadband LTE service provision at speed with a high frequency and a high data rate. Plotted are the NPVs resulting from factors of one (i.e. if no additional ground stations were required, and therefore it sufficed to upgrade existing GSM-R stations to support LTE); two (i.e. it would be necessary to deploy double the existing number of stations to reduce the distance among them by half) and three (likewise, two new stations should be built from the ground up for every existing upgraded GSM-R station). The highest NPV results from a factor of one, with the lowest resulting from a factor of three. Higher integer factors would result in a negative NPV compared to current GSM-R or equivalent GSM-family solutions.

More broadly, there is a significant difference regarding costs when comparing narrowband and broadband solutions. When considering broadband, SATCOM technologies must invest in higher frequency and more directional antennas increasing both complexity and cost, affecting primarily Railway Undertakings. Regarding terrestrial solutions, particularly LTE, new ground stations and infrastructure shall be deployed involving an important investment from the Infrastructure Managers side. Nevertheless, broadband solutions open a completely new source of revenue and the potential ROI.

Inside of the narrowband option, SATCOM solutions such as Iridium NEXT, Inmarsat 4/6 and GEO / C-band (in addition to a hypothetical MEO / C-band candidate) have shown that they could potentially exceed the economic performance of LTE, TETRA and GSM-family technologies. SATCOM narrowband solutions are similar, as the terminal costs[13] do not vary significantly between solutions and the tariffs are more or less the same.

In stark comparison, narrowband SATCOM candidate technologies come out as strong candidates compared to TETRA from a business perspective. The strong point of TETRA is its low operating frequency requiring a notably smaller number of stations and having a potential reutilization rate from

[13] As an illustrative cost values, narrowband SATCOM terminals are around 10k€, and broadband SATCOM terminals around 100k€.

public safety infrastructure. However, this reduced number is offset by the significantly higher cost of these stations for deployment and maintenance. Moreover, since TETRA has a very narrow bandwidth, it provides virtually no scope for value-added services due to its very limited data rates.

Regarding the broadband option, GEO/Ka-band shows to be the most competitive broadband SATCOM solution in terms of economic value over time. When considering the full NPV shown above, which includes the revenues obtained by railway undertakings from passenger-focused value added services, the total NPV exceeds current GSM-R values by over 18.000 M€ over just 15 years of operation (this is, the nominal stated lifecycle for the GSM-R successor without any life extensions). SmartLNB trails this value by a moderate margin.

As a consequence, a broadband SATCOM solution would prove a wiser business choice than LTE if the latter's deployment required more than doubling the existing network of GSM-R stations.

9.3.3.2.1 Stakeholders cost share

When analysing costs it is crucial to determine sources of expenses and how costs impact on each of the stakeholders. The figure below shows the cost distribution for each stakeholder depending on each technical solution.

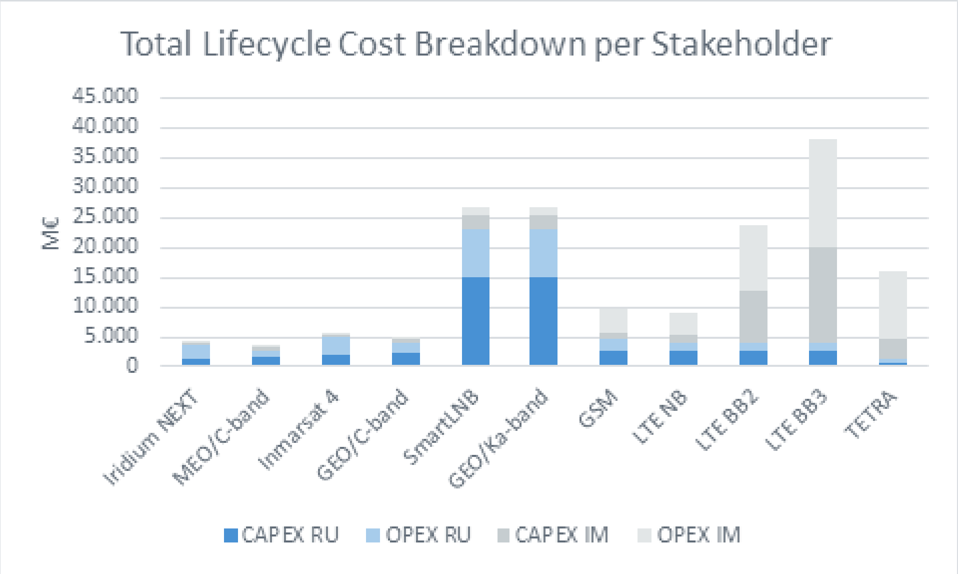



Figure 81: Stakeholders' cost share per category (LTE shown for the three different implementations explained below)

| | Railway Undertakings | | Infrastructure Managers | | Total Cost (M€) |
|---|---|---|---|---|---|
| | CAPEX (M€) | OPEX (M€) | CAPEX (M€) | OPEX (M€) | |
| Iridium NEXT | 1.219 | 2.470 | 391 | 244 | 4.324 |
| MEO/C-band | 1.560 | 1.217 | 460 | 281 | 3.518 |

| | | | | | |
|---|---|---|---|---|---|
| Inmarsat 4/6 | 1.997 | 2.879 | 391 | 244 | 5.512 |
| GEO/C-band | 2.485 | 1.475 | 575 | 341 | 4.876 |
| SmartLNB | 14.961 | 7.961 | 2.531 | 1.368 | 26.821 |
| GEO/Ka-band (BB) | 14.961 | 8.025 | 2.531 | 1.368 | 26.884 |
| GSM-R | 2.695 | 2.002 | 1.109 | 3.880 | 9.685 |
| LTE (NB, 900 MHz) | 2.695 | 1.417 | 1.109 | 3.880 | 9.100 |
| LTE (BB, 2.000 MHz, 2x deployment) | 2.695 | 1.417 | 8.499 | 11.058 | 23.668 |
| LTE (BB, 2.000 MHz, 3x deployment) | 2.695 | 1.417 | 15.889 | 18.235 | 38.236 |
| TETRA | 502 | 727 | 3.310 | 11.584 | 16.122 |

Table 37: Breakdown of costs in CAPEX and OPEX per solutions shown in Figure 81

Terrestrial solutions have a higher infrastructure investment as they require the maintenance or deployment of several costly base stations. Thus, the infrastructure manager is allocated the majority of the costs. In the case of SATCOM solutions, it is a completely different scenario; the key cost driver in this case is the terminal cost. Thus, the infrastructure manager and the rail undertaking share the cost evenly, except for the broadband solutions, where the terminal cost is much higher and railway undertakings are allocated the major part of the costs.

It is also clear that SmartLNB or GEO Ka-band are much more expensive to implement with higher CAPEX and OPEX costs, mainly because of the expensive terminals and directive antennas required for providing the service. LTE could operate at a frequency of over 2.000 MHz ad at a high data rate at the expense of requiring a high investment in newly-deployed ground stations, thus markedly increasing the cost of LTE infrastructure. As mentioned before, the cost of LTE is highly dependent on the need to deploy such stations in addition to the existing, upgradeable GSM-R network. Nevertheless, for all three broadband solutions, lifecycle costs are offset by revenues (except for conservative estimates of LTE deployment), therefore resulting in positive NPVs despite the high lifecycle costs shown in the figure above.

#### 9.3.3.2.2 Case Study: What if voice were not a requirement?

An interesting factor in the business case is considering whether voice is a requirement or not, since voice is not a strict legal requirement for critical services in railway. However, it is a service currently provided by GSM-R. Voice is a challenge for SATCOM communications due to several technical issues, and if it were not a requirement, SATCOM solutions would significantly reinforce their position.

The following assumptions have been considered to model this scenario:

- Voice communications are assumed to migrate to less bandwidth-consuming data services. Hence, handheld terminals would not be required, lowering CAPEX, while OPEX would also come down as well, since it is dominated by voice communications

As expected, the results, as presented in section §9.3.4, show that this scenario would render SATCOM solutions more competitive, since they would not be penalized by the voice communication fees or by the use of costly handheld devices.

In this positive business case, combined with the high compliance with the rest of technical requirements, would potentially make Iridium NEXT or Inmarsat 4/6 very serious contenders for a GSM-R replacement.

#### 9.3.3.2.3 Break-even with revenue-generating value-added services

First of all, the global NPV (Net Present Value) evolution for broadband solutions will be presented compared to GSM-R. The NPV has been computed as a result of adding the revenues to the expenses originating from technology implementation.

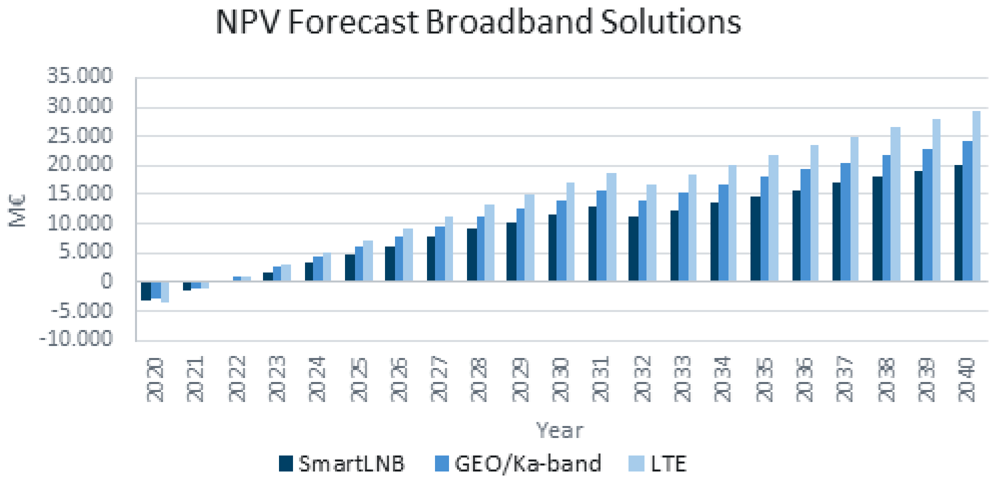



Figure 82: Absolute NPV evolution broadband solutions (compared to GSM-R)

For the above analysis, a moderately optimistic implementation has been considered for LTE, assuming that the number of existing, upgradeable GSM-R stations should be doubled.

As seen above, in the long run, GEO/Ka-band is the most competitive broadband SATCOM option, only trailing the most optimistic implementations of LTE by a very close margin, with an IRR of 72% compared to the latter's 70% (with an NPV by 2035 of €18.100 M compared to LTE's €21.900 M, which can be taken as a reference. In comparison, SmartLNB involves higher communication fees, which hinders its competitiveness compared to GEO/Ka-band, yielding an NPV of €14.700 M by 2035 and an IRR of 57%. It must be taken into account that, despite this, both solutions would provide a stronger overall business case compared to today's GSM-R.

Regarding break-even points, they occur early on for all solutions compared to the current GSM-R platform, essentially thanks to the revenues generated by the value added services available to passengers. All broadband solutions break-even points would take place in 2022.

It can be seen that the growing value trend is interrupted in 2032, when a modetrate dip occurs due to the need to renew all infrastructure and terminal devices at the end of their 12-year service life. This re-investment would be recovered in 3-4 years, when the value would exceed the 2031 levels.

9.3.3.2.4 Costs

The cost analysis shown in this section only contemplates the costs emerging from providing value-added services via broadband solutions, as opposed to the use of the same solutions to provide only safety-critical voice and data communications.

On the one hand, broadband SATCOM solutions would require small upgrades in terms of infrastructure, since the main cost driver, *i.e.* the terminal devices, are already broadband-grade even for a safety-critical-only implementation, and do not require any updates. Only on-board Wi-Fi repeaters would be required as a supplemental asset. Hence, equipment costs are relatively small compared to the tariffs to be paid for providing the service. This leads to an OPEX-driven cost model. All the costs resulting from providing broadband services are incurred by the railway undertaking.

On the other hand, LTE presents a stark contrast with SATCOM. When compared to a safety-critical-only narrow or medium-band implementation for LTE, a broadband revenue-generating solution supporting value added services would require a much more ambitious deployment, as explained in the previous sections. Therefore, all incremental costs concepts incurred when deploying a broadband LTE network compared to a medium or narrowband one, should be attributed exclusively to the need to provide such revenue-generating value added services.

These incremental costs entail mainly the need to deploy additional, new-build base stations, increasing the existing GSM-R network by a factor of up to four. This cost would be incurred by the infrastructure manager, which is assumed to be able to recover all or part of this investment through utilisation fees charged to the railway undertaking. Nevertheless, this interaction has not been assessed in the model. Furthermore, the railway undertaking would be responsible for the train-board equipment and bandwidth tariffs, which are considerably lower than SATCOM.

Figure 83 shows the cost distribution in terms of CAPEX and OPEX for each technology assessed.

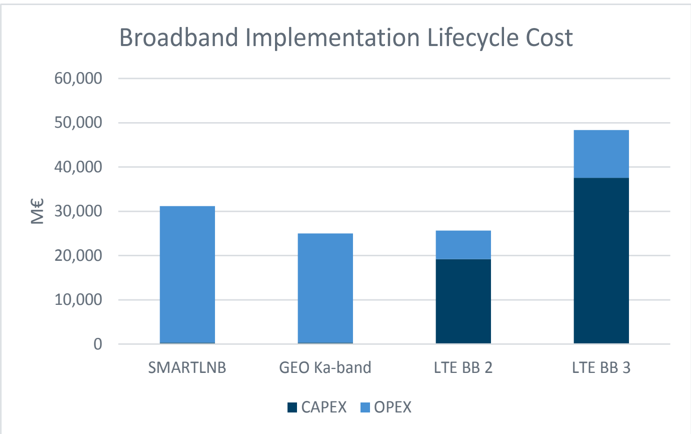


Figure 83: Cost segmentation per solution

As seen in the figure, SATCOM solutions costs are driven by OPEX (especially on the railway undertaking's side), while in LTE, costs are dominated by CAPEX, especially affecting the infrastructure manager.

9.3.3.2.5 Revenues

As mentioned previously, only one source of revenues has been considered, in the form of the user tariff. This tariff is a fixed price per user and travel. The tariff price is not influenced by macro-economic parameters such as inflation. Additionally, railway demand increases with the population. Therefore, the revenues obtained rise over the years, as shown below.

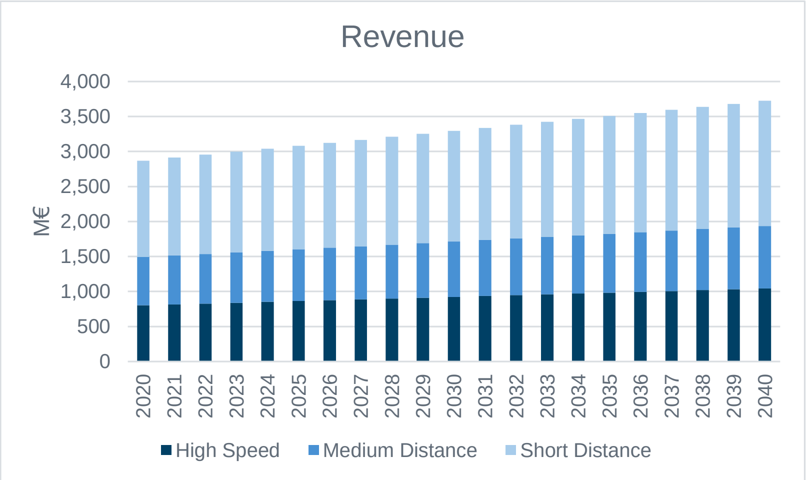



Figure 84: Revenue incomes forecast

### 9.3.4 Sensitivity Analysis

This section is aimed at determining which parameters would induce a significant change into the results should they face a small variation. This serves to illustrate the solidity and robustness of the model, as well as the key drivers in possible cost variations in a real-life scenario. Hence, it provides a good measure of the uncertainty involved in this analysis.

#### 9.3.4.1 Approach of the analysis

The approach followed in performing the analysis consists of varying the value of a parameter by a fixed percentage and identifying how this variation influences the final result. In the case of Boolean parameters, *yes* or *no*, *no* is taken as baseline, since this would make it analogous to GSM-R's current functions. The parameters assessed within the scope of the project are the ones listed below:

- **Broadband** is used as a Boolean parameter that indicates whether value-added services are included in the model. This parameter will be assessed as a secondary baseline, as it affects the model significantly, even modifying the pool of possible candidates.
- **Re-use factor parameter** describes the infrastructure re-utilisation for terrestrial implementation.
- **Voice** parameter is used as a Boolean that indicates whether voice is a strict requirement for the service provision.
- **Terminal prices** play an important role when defining the costs.
- **Communication tariffs** gain relevance when providing broadband services.
- **Value-added tariffs or services usage** size the income from value-added services and therefore determine its feasibility. Both multiply each other, and percentage changes have the same effect on the NPV. This parameter is only available for the broadband baseline.

There are other relevant parameters that may impact significantly on the overall result. Nevertheless, they have been discarded, as their value is either confidently known, or they are related to the parameters analysed, e.g. the base station unitary price, apart from being available from the benchmark, is somehow related with the re-use factor as both are multiplied in the final formula.

#### 9.3.4.2 Narrowband solutions analysis

Here the results of the sensitivity analysis are presented for each technology considering only narrowband services.

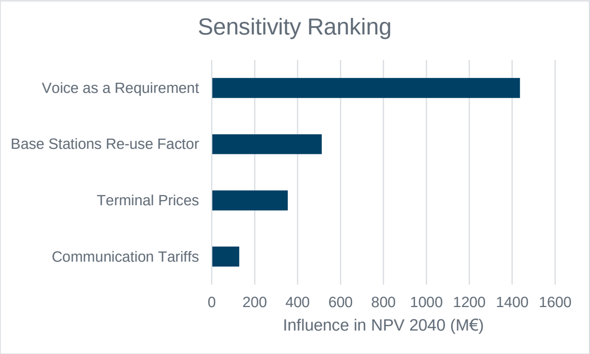



Figure 85: Narrowband sensitivity parameters ranking

The sensitivity ranking has been built not according to the maximum influence on the results, but rather the most relevant. An illustrative example of the rationale is presented below.

TETRA presents much higher sensitivity than LTE regarding the re-use factor parameter. However, considering the overall results, LTE shows a better overall business case than TETRA, and therefore it appears as a much more relevant solution than TETRA.

The objective of the sensitivity ranking is to state which parameters have more influence in the most relevant solutions. Therefore, the parameters have been ranked keeping a balance of their influence and the solution affected. Thus, this ranking represents the parameters that have most influence on the most plausible future scenarios.

Figure 86 shows a detailed breakdown of the sensitivity analysis per solution.

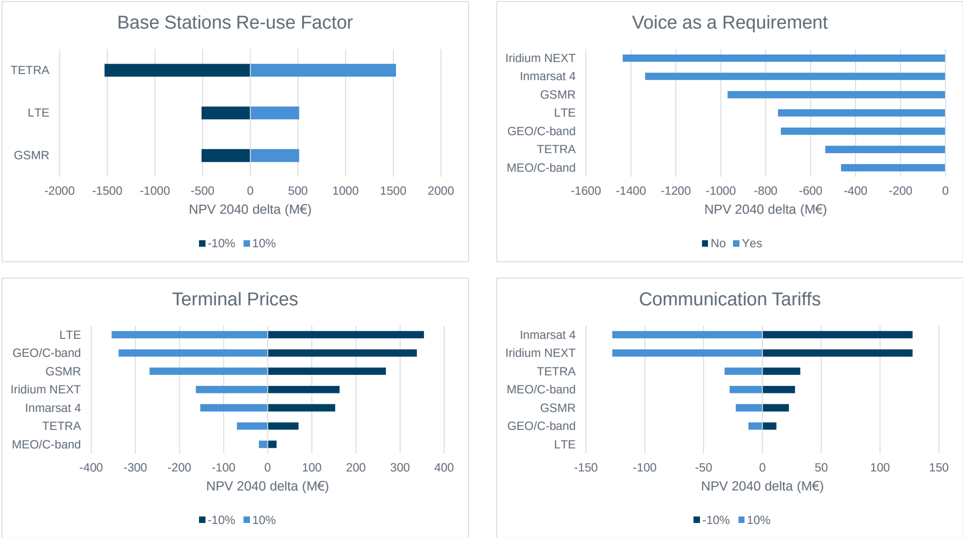



Figure 86: Sensitivity analysis results for narrowband solutions

In the realm of narrowband solutions, voice is the parameter that induces the highest sensitivity. It has an especially great influence on SATCOM narrowband solutions Iridium NEXT and Inmarsat 4. Furthermore, not only does voice impose a strict cost penalization, but it also adds complexity to the technical solution.

The second most sensitive parameter is the re-use factor which is directly proportional to the number of stations required to provide the service. Therefore, TETRA, the technology operating at lowest frequency and having more base stations, is the most influenced by this parameter.

Terminal prices hold third position in the ranking. Reducing this cost will benefit mainly terrestrial solutions which are currently the ones with highest cost per terminal apart from broadband services, which are not assessed here.

Lastly, the value of the communication tariffs has a higher impact on Inmarsat 4 and Iridium NEXT, these two options being the strongest competitors to terrestrial solutions.

#### 9.3.4.3 Broadband solutions analysis

In this section the results of the sensitivity analysis for each technology are presented taking only broadband services into account.

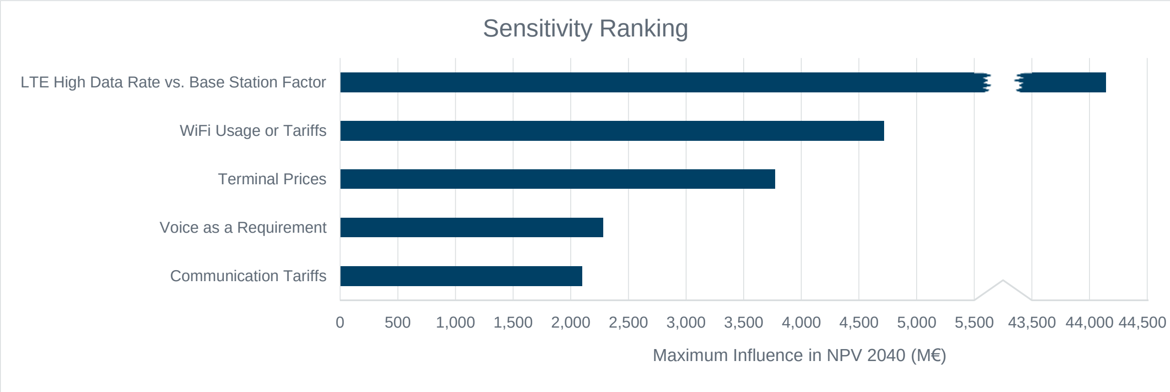



Figure 87: Broadband sensitivity parameters ranking

It is clear that the strongest sensitivity of all, by one order of magnitude, is the LTE high data rate linked to the labelled “base station factor”, i.e. the need to deploy new-build LTE stations by a given factor over the existing (upgradeable) GSM-R network to ensure adequate performance at speed for high data rate and high frequency communications. This, however, is not an intrinsic sensitivity for SATCOM solutions, albeit it does affect their positioning in the market and their competitive business case.

The model is also highly sensitive to the revenues obtained through the services. These revenues will determine whether the investment is recovered and there is some uncertainty about the tariffs that the users are willing to pay, although the model is flexible and realistic values have been used.

Terminal prices are the third-ranked parameter in the sensitivity analysis, mainly because of the heavy prices of SATCOM terminals.

Voice as a requirement in third place is closely followed by communication tariffs, which also represent a key driver for the model.

Figure 88 shows a detailed breakdown of the sensitivity analysis per solution.

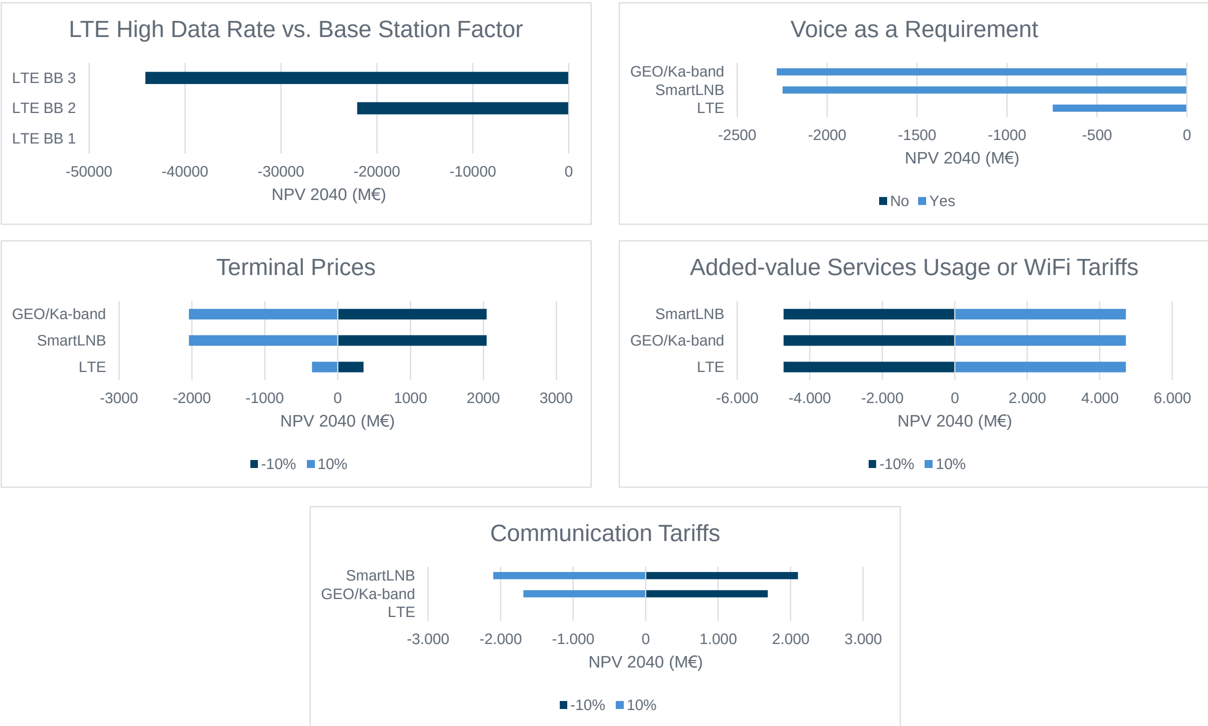



Figure 88: Sensitivity analysis results for broadband solutions

First of all, as mentioned before, it can be seen that the re-use factor only affects LTE, since it is the only terrestrial option considered for broadband. However, it has the largest impact of all within a window of high likelihood. Moreover, despite affecting only LTE, it impacts the competitiveness of SATCOM candidates when benchmarked against their key competitor.

As far as revenues are concerned, broadband services' usage or Wi-Fi Tariffs modifications are independent from the technology used to provide the service because of the split between costs and revenues in these two completely different models – SATCOM and terrestrial mobile technologies.

Moreover, terminal prices have a strong effect on SATCOM broadband solutions. This is because SATCOM broadband terminals are far more expensive than those for LTE.

The consideration of voice as a requirement affects SATCOM solutions primarily, and plays a heavy role in costs.

Finally, the model is notably sensitive to communication tariffs, which are a main driver for the costs in SATCOM broadband representing the main source of expenses for these solutions.

#### 9.3.4.4 Conclusions and Key Sensitivities of the Analysis

Figure 89 shows the parameters that have most influence on each stakeholder's economic prospects, depending on the solution.

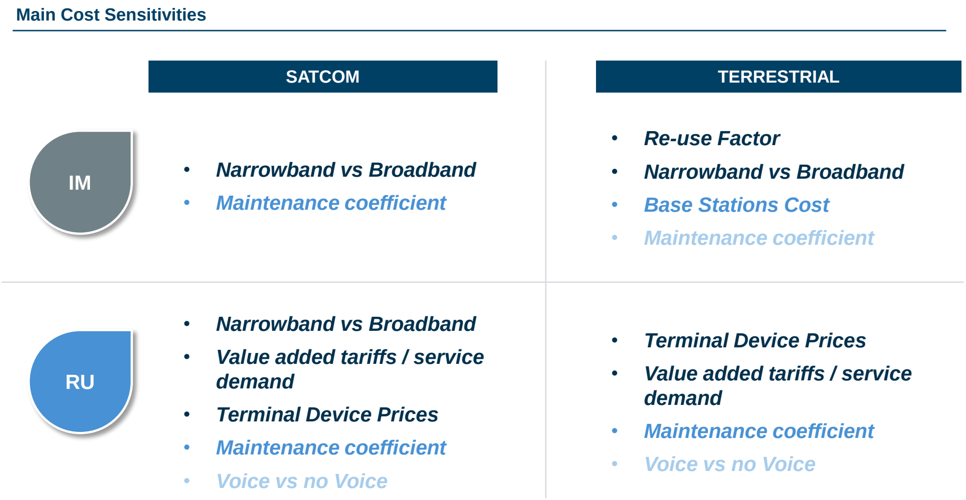



Figure 89: Sensitivity matrix

The most significant sensitivity of the analysis arises from service type chosen, broadband or narrowband. This is amplified by the strong uncertainty in the need to deploy additional LTE ground stations to support broadband implementations at high frequency and data rates.

For SATCOM solutions, the price of terminals is the main driver for the costs due to its very high value, particularly when considering broadband, an option which severely increases the device price.

As far as terrestrial solutions are concerned, the main parameters affecting the costs are the previously mentioned deployment factor for the base stations (which is of a higher order of magnitude for broadband applications due to the high frequency and high data rate factor, but still exists in narrowband solutions due to the uncertainty in the upgrade costs from base stations to transition from GSM-R to LTE); as well as the base station cost and the total number of stations, which is dependent on the frequency at which the solution functions.

Another high-sensitivity parameter is the maintenance coefficient that determines the operational expenses required to maintain all the infrastructure and terminals.

Furthermore, considering voice as a requirement has a strong impact on cost, but is also an important influence in technical compliance for the SATCOM solutions.

Finally, the value-added tariffs/service usage parameter is the only variable that generates revenues to compensate for the overall investment, and is therefore the parameter with highest impact in the sensitivity analysis.

### 9.3.5 Assessment and compliance matrix of the non-technical and non-functional criteria

This section is devoted to identifying whether the proposed solution complies with the non-technical requirements or criteria.

Table 38 shows the non-technical and non-functional criteria defined previously in section §5.

| Criterion ID | Criterion | Parameters |
|---|---|---|
| **CRT-NONT-1** | The proposed SATCOM system for the future railway communications architecture shall have a universally assumed sustained lifecycle covering the total timespan of the FRMCS without risk of obsolescence. | Sustainability |
| **CRT-NONT-2** | The proposed SATCOM system for the future railway communications architecture shall provide for easy serviceability that has minimal impact on operations, whether it is due to scheduled or unscheduled maintenance/repair. However, during preventative or corrective maintenance, the subsystem may not be able to respect the values quoted in the Basic Parameters; the maintenance rules shall ensure that safety is not prejudiced during these activities. | Serviceability |
| **CRT-NONT-3** | The proposed SATCOM system for the future railway communications architecture shall provide at least an acceptable level of cost efficiency, taking into account full lifecycle costs covering the full lifespan of the selected solution, and as long as technical and functional requirements allow for this option. | Cost |
| **CRT-NONT-4** | The proposed SATCOM system for the future railway communications architecture shall demonstrate forecasted full lifecycle costs that are, by all acceptable estimates, lower than those of GSM-R. | Cost |
| **CRT-NONT-5** | The proposed SATCOM system for the future railway communications architecture shall demonstrate a forecasted full lifecycle economic internal rate of return (IRR, alternatively ERR) above the average minimum acceptable rate of return (MARR) set by the target Member States for public investments. | Cost |
| **CRT-NONT-6** | The proposed SATCOM system for the future railway communications architecture shall comply with the specific railway certification standards. | Certification |
| **CRT-NONT-7** | The proposed SATCOM system for the future railway communications architecture shall hold at least a universally accepted technology readiness level (TRL) of 7 or above. | Maturity |

Table 38: Relation between non-functional and non-technical criteria and parameters

#### 9.3.5.1 Horizontal assessment

The following table defines the assessment criteria used to evaluate each solution.

| Criterion ID | Criterion | Rationale |
|---|---|---|
| **CRT-NONT-1** | *Fully Compliant* | There are planned projects to use this technology or maintain it for the whole time span |
| | *Partially Compliant* | There are planned projects to use this technology or maintain it for almost the whole time span |
| | *Not Compliant* | There are no planned projects to use this technology or maintain it, or it covers just a small portion of the time span |
| | *Not Applicable* | This criteria has not been assessed |
| | *Unknown* | The results from the assessment are uncertain |
| **CRT-NONT-2** | *Fully Compliant* | The technology has important characteristics that support easier maintenance, such as the absence of parabolic antennas. |

| | | |
|---|---|---|
| | *Partially Compliant* | The technology maintenance is acceptable considering the current market and pool of candidates |
| | *Not Compliant* | The technology involves unacceptably high investments, down time and/or complexity to maintain the system |
| | *Not Applicable* | This criteria has not been assessed |
| | *Unknown* | The results from the assessment are uncertain |
| **CRT-NONT-3** | *Fully Compliant* | The technology is understood by all acceptable estimates to be deployable within 10 years' time starting on the date of publication of this study |
| | *Partially Compliant* | The technology  is likely to be deployable within 10 years' time with small effort |
| | *Not Compliant* | The technology is by all estimates impossible to be deployed within 10 years' times |
| | *Not Applicable* | This criteria has not been assessed |
| | *Unknown* | The results from the assessment are uncertain |
| **CRT-NONT-4** | *Fully Compliant* | After the cost-benefit analysis, the full lifecycle cost associated with this technology is lower than GSM-R |
| | *Partially Compliant* | After the cost-benefit analysis, the full lifecycle cost associated with this technology is likely to be lower, but within a close margin from GSM-R |
| | *Not Compliant* | After the cost-benefit analysis, the cost associated with this technology appears to be clearly higher than GSM-R |
| | *Not Applicable* | This criteria has not been assessed |
| | *Unknown* | The results from the assessment are uncertain |
| **CRT-NONT-5** | *Fully Compliant* | The IRR for the full lifecycle cost compared to GSM-R is higher than 4% |
| | *Partially Compliant* | The IRR for the full lifecycle cost compared to GSM-R is higher than 3% |
| | *Not Compliant* | The IRR for the full lifecycle cost compared to GSM-R is lower than 3% |
| | *Not Applicable* | This criteria has not been assessed |
| | *Unknown* | The results from the assessment are uncertain |
| **CRT-NONT-6** | *Fully Compliant* | The technology could meet railway certification standards with minimal or no modification |
| | *Partially Compliant* | The technology could likely meet railway certification standards with some modification |
| | *Not Compliant* | The technology could likely not meet railway certification standards |
| | *Not Applicable* | This criteria has not been assessed |

| | | |
|---|---|---|
| | *Unknown* | The results from the assessment are uncertain |
| **CRT-NONT-7** | *Fully Compliant* | The technology holds a TRL superior to 7 |
| | *Partially Compliant* | The technology holds a TRL6 and it is close to reaching TRL7 |
| | *Not Compliant* | The technology holds a TRL lower than 6 |
| | *Not Applicable* | This criteria has not been assessed |
| | *Unknown* | The results from the assessment are uncertain |

Table 39: Horizontal assessment criteria of the non-technical requirements

General comments:

- **CRT-NONT-1** is an achievable criterion with a wide range of complying solutions. It is also a useful criterion as it discards the solutions that have not been developed yet and reduces the pool of plausible candidates.
- **CRT-NONT-2** shows that there is still a gap for improvement regarding maintainability. The majority of SATCOM solutions require parabolic antennas introducing more vulnerability to the system and increasing maintenance requirements. This is even more relevant in broadband solutions.
- **CRT-NONT-3** assesses whether or not the solutions proposed are efficient within the existing infrastructure. It is regarded that this criterion is easily achievable by the majority of the solutions.
- **CRT-NONT-4**, as an economic criterion, is positive for all the candidates when compared to the GSM-R baseline. The solutions labelled N/A have not been assessed within the scope of the cost-benefit analysis.
- **CRT-NONT-5** shows an equivalent result to **CRT-NONT-4**.
- **CRT-NONT-6** shows that the majority of the candidates will require a slight modification in the design to comply with the certification standards imposed by the railway sector. However, it appears as an achievable target and it shows full compliance for the theoretical, non-deployed solutions, which have been assumed to be designed from the ground up for railway use.
- **CRT-NONT-7** shows the solutions proposed have sufficient technology readiness to operate the services, apart from MEO C-band and GEO L-band +Antares, which have not been developed yet and are considered as potential solutions based on their technical features.

Special attention will be paid to Iridium NEXT, which partially complies with CRT-NONT-1. This is due to the fact that the provider ensures its services until 2032, even though it is expected to keep working beyond this date. It is also worth pointing out that future planned technologies such as GEO L-band + Antares CS (within the IRIS FOC) or even hypothetical solutions such as the MEO C-band, are assumed to comply fully with certification standard criteria. As pointed out before, this is due to the fact that in the case that those technologies were developed (or adopted) for the railway purpose, those technologies would incorporate the certification standards compliance as a requirement in the design.

#### 9.3.5.2 Vertical assessment

In the list below, a vertical analysis of each technology's compliance is presented.

- **Iridium Next** is a 66-satellite LEO constellation providing communication services in L and Ka bands. It is expected to be fully deployed by 2017 with a life expectancy of 15 years. Thus, it will be operative until 2032. Currently, Iridium Next possess a TRL ≥ 7 and its ground terminals were successfully tested in 2016. Iridium communications require small-sized non-directional (*i.e.* hemispherical) antennas, which involve easy maintenance. Iridium is expected to comply with railway certification standards, requiring only minor development and modifications. Furthermore, Iridium Next provides IP based services, which allow meeting multi-technology criteria.
- **MEO C-band** is considered as a possible theoretical solution and provides one of the more balanced and appropriate set of features for the railway scenario. There are no current solutions nor planned projects to develop this technology. Deploying and integrating a fully MEO C-band system under 10 years is considered unfeasible. MEO C-band possess a TRL between 2 and 3. MEO C-band communications require small-sized hemispherical antennas, which involve lower maintenance cost. MEO C-band solutions will be designed such as comply railway certification standards.
- **Inmarsat 4/6** is a 3-satellite GEO constellation providing communication services in L band. I-4 is currently operative and I-6 is being developed. The first I-6 satellite is scheduled for launch by 2020 and has a lifetime of 15 years, so it will be operative until 2035. Currently, Inmarsat 4 possesses a TRL 9. Inmarsat 4/6 communications require small-sized hemispherical antennas, which involve lower maintenance costs[14]. Inmarsat is expected to comply with railway certification standards, requiring only minor development and modifications.
- **GEO L-band plus ANTARES (IRIS FOC)** is a solution of a GEO constellation using the ANTARES communication standard. The IRIS FOC system (on development under the ESA ARTES 10 program) is expected to comply with the whole set of requirements considered for the ANTARES CS, although from 2025. IRIS FOC communications will require small-sized hemispherical antennas, which will involve lower maintenance cost. The system is assumed to be well sized and scalable to cover the future railway demand. IRIS FOC, if modified accordingly for railways, should be designed to comply with future railway certification standards.
- **Thuraya** is a 2-satellite GEO constellation providing communication services in L band. The end of the current satellites' lifecyle is expected by 2020. However, Thuraya has started a fundraising campaign to launch new satellites and continue the service. Currently, Thuraya possesses a TRL 9. The current solution can comply with railway certification standards, requiring only some modifications.
- **GEO S-band** technology is available and currently operated by Eutelsat, Astra and Europasat. Its operation is expected to continue at least until 2027. GEO S-band possesses a TRL 9. GEO S-band communications require small-sized hemispherical antennasantennas, which involve lower maintenance costs. Furthermore, the current terminals and commercial solutions could comply the rail certification standards, requiring only some modifications.

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[14] I4 can provide low profile small-sized directional antenna depending on service type.

- **GEO C-band** is a technology that has been used for providing broadband services outside Europe. There exists strong pressure from the terrestrial mobile communication industry to transfer lower part of C-band, currently for SATCOM use, to terrestrial ones. At this moment, there exist several European initiatives (*e.g.* from ESA, EUROCAE, etc) in order to find out the most suitable bearer able to allow sharing this band for both, RLOS and SATCOM. It is known that there exist some proposal for this type of bearer; however, this information is not public. GEO C-band possesses a TRL 9. GEO C-band communications require medium-sized hemispherical[15] antennas, which involve medium maintenance cost. Furthermore, the current terminals and commercial solutions could comply with the rail certification standards, requiring only minor modifications.

- **GEO X-band** is a technology currently reserved for the government and military institutions. An example of this type of solution is GOVSAT[16]. It is scheduled to be operational by Q4 2017 with a continued service. GOVSAT has a TRL equal or higher than 7. GEO X-band communications require medium-sized directional steerable antennas, which involve higher maintenance cost. It is a highly secure satellite with encrypted command and control and anti-jamming capabilities and will easily comply with the rail certification standards, requiring only minor modifications.

- **SmartLNB** is a GEO constellation providing communication services in Ku/Ka-band. The technology will likely remain operative during the following decades due to its commercial applicability. SmartLNB communications require medium-sized directional steerable antennas, which involve higher maintenance costs. SmartLNB possess a TRL 9. Furthermore, the current terminals and commercial solutions can comply with the rail certification standards, requiring only some modifications.

- **GEO Ku-band** is a technology currently used for commercial purposes. The technology will likely remain operative during the following decades. GEO Ku-band communications require medium-sized directional steerable antennas, which involve higher maintenance cost. It possesses a TRL 9. Furthermore, the current terminals and commercial solutions can comply with the rail certification standards, requiring only some modifications.

- **Inmarsat 5** is a 3-satellite constellation in GEO providing communication services in Ka-band. It was completely deployed in 2015 and has a lifetime of 15 years. Thus, it will be operative until 2030. Inmarsat 5 possesses a TRL 9. Inmarsat 5 communications require medium-sized directional steerable antennas, which involve higher maintenance costs. Furthermore, Inmarsat 5 provides IP based services that allow meeting multi-technology criteria.

#### 9.3.5.3 Compliance matrix

Therefore, taking into account CBA of previous sections and justifications for each evaluated technology above, Figure 90 shows the evaluation result of the non-technical and non-functional criteria.

[15] This case is only considering support for critical applications, but If broadband services were included, then it would be needed to use high-sized steerable directional antennas.

[16] GOVSAT is going to provide services in X-band and also Ka-band, especially for GOVSATCOM applications

| Criterion ID | Satcom technology | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| | Iridium NEXT | MEO / C-band | Inmarsat 4 (BGAN) - Inmarsat 6 (ICE) | IRIS FOC | Thuraya | GEO / S-band | GEO / C-band | GEO / X-band | SmartLNB | GEO / Ku-band | Inmarsat 5 (Global Xpress) |
| CRT-NONT-1 | PC | NC | C | NC | PC | PC | C | C | C | C | PC |
| CRT-NONT-2 | C | C | C | C | C | C | C | PC | PC | PC | PC |
| CRT-NONT-3 | C | NC | C | PC | C | C | C | C | C | C | C |
| CRT-NONT-4 | C | C | C | N/A | N/A | N/A | C | N/A | C | C | N/A |
| CRT-NONT-5 | C | C | C | N/A | N/A | N/A | C | N/A | C | C | N/A |
| CRT-NONT-6 | PC | C | PC | C | PC | PC | PC | PC | PC | PC | PC |
| CRT-NONT-7 | C | NC | PC | NC | C | C | C | C | C | C | C |

Figure 90: Non-technical and non-functional criteria compliance matrix

## 10. OPERATIONAL AND DEPLOYMENT CONDITIONS

When a communication system is introduced into a new environment, and once technical and non-technical requirements have been assessed, some other factors related to **operational and deployment conditions** shall be addressed to assure the success of the selected solution.

In this case, where SATCOM solutions are the only ones analysed to be introduced into the railway domain, these operational and deployment conditions are of vital importance since, for instance, one solution could be feasible from the technical point of view, but it could be a invalid depending on the scenario.

Due to specific SATCOM solutions characteristics, its application on the railway domain can bring some interesting advantages, such as the quick deployment on existing lines. On the contrary, SATCOM also entails some drawbacks that can limit its deployment to some specific scenarios, such as the continuous visibility required to the satellite in order to operate properly.

Hence, propitious **scenarios for SATCOM for railways** can be:

- ***High Speed Lines (HSL)***. This scenario is characterised for a high mobility speed and a small number of users. Distance between train stations is usually large.
- ***Regional Lines***. Similar to HSL but with a lower mobility speed and a smaller distance between train stations. In this case, satellite solutions could enable the use of ETCS to those lines where GSM-R has not been deployed because of economic deployment reasons.

In both scenarios (HSL and Regional lines), main part of the route is between cities and, therefore, with a higher possibility to have a good satellite coverage along the route, reducing this way the part of the route to be covered by additional gap fillers or land based terrestrial solutions.

These scenarios coincide (to some extent) with the ones obtained from the survey conducted in this study (see section §7). In this survey, a high percentage of rail stakeholders respondents (81%) considered that SATCOM may play an important role as part of the FRMCS, either as a complementary system for some scenarios, a backup system or a backhaul. And the same percentage of rail participants in the survey considered that SATCOM would be well-suited for **low-density/regional lines**, with a limited number of users and moderate-to-high speed. On the contrary, high-speed lines scenario got a low value (33%), which contrasts with the fact that SATCOM tends to cope better with high-speeds drawbacks (such as Doppler) than terrestrial solutions.

Therefore, taking into account previous scenarios propitious for railways, following aspects are highlighted in order to be considered in the SATCOM for railways environment:

- ***Satellite visibility (coverage)***. It is probably the main aspect to have in mind when going to deploy a SATCOM solution for a mobile scenario in general, and in a railway environment in particular. This feature is directly related with the *satellite elevation angle* aspect, since depending on the SATCOM solution chosen, some areas to be covered by SATCOM could have a too low elevation angle and, in consequence, a poor satellite visibility where any urban or rural element could become an obstacle.
- ***Satellite elevation angle***. Just as it has been explained before, this aspect is directly related with the satellite visibility or coverage. With SATCOM solutions where satellites are not static (*i.e.* LEO and MEO constellations), a good and homogeneous satellite elevation angle can be assured along the whole area to be covered by the SATCOM solution. But with GEO constellations,

northern part of Europe would have low satellite elevation angles that would make this solution unfeasible[17].

- ***Off-axis***. An important factor to keep in mind when designing a mobile SATCOM solution (i.e. with low profile antennas) if the off-axis compliance, which refers to the power density radiated in any direction from a certain angle (usually from 2.5º). This parameter refers directly to the antenna design, and the maximum off-axis value is regulated by ITU. To fulfil with such regulations adequate measures shall be implemented in order to be homologated by the satellite operator. Most of times, it is fixed by spreading the signal using more robust modcod (lower modulation and/or coding rate) or using a spreading sequence to reduce the power spectral density.
- ***Vertical handovers*** (in a multi-technology environment)[18]. FRMCS (Future Railway Mobile Communications System) will consist of several communications systems, just like NGN (Next Generation Networks) trends show. One of these systems could be a SATCOM solution, used especially for some concrete scenarios or as a backup or complementary system (for example). But regardless of whether SATCOM is used or not, the capacity to perform vertical handovers (*i.e.* handovers between communications systems) is required in the FRMCS in order to switch to other communication technology when necessary. A *smart router* could be in charge of performing these handovers, since it is an intelligent element capable to monitor all the networks enabled and perform the switch among them when required.
- ***Railway certification for SATCOM equipments***. Since all on-board railway equipment shall be certified according to railway standards and rules established, SATCOM equipment shall also be certified according to railways normative (*e.g.* EN50155, etc).

[17] HEO constellations can become in a good solution for these more northern areas (i.e. near polar area) as for example Molnya and Tundra.

[18] Despite vertical handovers have been considered in multi-technology criteria, they have not been evaluated because it applies to final architecture design and operational conditions.

# 11. CONCLUSIONS AND RECOMMENDATIONS

## 11.1 MAIN FINDINGS

This section provides findings regarding **technical**, **multi-technology** and **non-technical criteria** based on the SATCOM solutions' assessment carried out in section §9.

### 11.1.1 Findings regarding technical criteria

After analysing the SATCOM solutions in previous sections, the following conclusions have been drawn:

- After the technical & functional criteria assessment, the theoretical system **MEO/C-band** is the best-positioned SATCOM solution.
- Other well-positioned SATCOM solutions (although with more requirements scored as non- or partial-compliant) are GEO/L-band (*e.g.* IRIS FOC), GEO/S-band and GEO/C-band.
- The most demanding criteria for SATCOM solutions are:
  - **Availability** for critical applications
  - **Transfer delay** between SATCOM remote terminals
  - The use of **handhelds**

These conclusions have been drawn after the assessment of only SATCOM solutions (*i.e.* without considering the behaviour of gap fillers and/or additional terrestrial systems) and by taking into account data and voice applications. If **only data applications** (*i.e.* ETCS) were considered, some criteria would not be necessary (such as the use of handhelds) and some others could be easier to comply by SATCOM solutions due to the reduced data rate (such as the link availability):

- When voice applications are not considered, data rate decreases and, therefore, link availability is largely increased.
- SATCOM communications will only consist of single hop connections (between ground stations and on-board SATCOM terminals). In this way, the transfer delay is reduced compared to with that of the double hop connectivity required for user-to-user (voice) connections.
- SATCOM handhelds, the most demanding type of terminals, would therefore no longer be required.

This hypothesis makes more feasible GEO solutions operating at low frequency bands (L, S and C bands), since their main constraints are the delay on double hop connections and the absence of handhelds.

It is worth mentioning that in the long term, the concept of operation in railways could change and voice services could be replaced by data applications, making possible the use of SATCOM solutions to support services currently provided by voice and data applications using only data. In addition, in the long term, there may be a SATCOM solution complying with both voice and data services (such as the MEO/C-band solution), being also possible this way to offer a SATCOM solution compliant with all the criteria identified.

### 11.1.2 Findings regarding multi-technology criteria

Regarding multi-technology criteria (where only the CRT-MULT-1 has been assessed), **all the SATCOM solutions evaluated are compliant**. This means that all of them are packet-switched networks, or at least part of their solution is based on packet-switched technology. In fact, some of the solutions assessed are exclusively based on a packet-switched method, and some others are both circuit-switched and packet-switched.

### 11.1.3 Findings regarding non-technical criteria

If only safety-critical data and voice services are considered, the most competitive value proposition is that of **narrowband solutions**. In this context, SATCOM solutions such as Iridium NEXT, Inmarsat 4/6 or GEO/C-band, as well as a hypothetical MEO/C-band, would be ideally suited as GSM-R replacements compared to the existing terrestrial communications, bearing in mind that:

- Such a competitive edge is dependent on the cost of terminals.
- SATCOM's competitiveness is dependent on the need to deploy new base stations for competing terrestrial technologies, such as LTE, compared to the current GSM-R deployment, which will be able to be reused by such mobile solutions.
- A future review of functional requirements to eliminate the need for voice communications would make the position of SATCOM solutions even stronger.
- Narrowband solutions would severely hinder the growing offering of value-added services by Railway Undertakings. Nevertheless, they could prove a suitable direct successor to GSM-R.

**Broadband solutions** expand the possibility to open new markets for the rail users generating multiple sources of revenue and being able to recover the strong initial investments required to provide the service. Broadband solutions are an especially good alternative for GSM-R replacement when considering that:

- The key assets (*e.g.* antenna) of SATCOM broadband solutions are their flexibility and scalability for deployment, together with their OPEX-intensive model. This is in contrast with the necessary CAPEX needed to upgrade LTE (the main broadband terrestrial technology) from a fully functional-focused deployment to a user added value-capable system.
- As a result, SATCOM could be deployed progressively and—to a considerable degree—by sharing costs among railway undertakings, while LTE would put a high burden on infrastructure managers, requiring the full coverage deployment for specific rail lines before reaching operational capability.
- Global economic results suggest that GEO/Ka-band could provide a competitive alternative to LTE while, at the same time, leverage the above assets. Comparatively, LTE could provide either a stronger or a significantly weaker business case, depending on the need to deploy additional new-build ground stations in order to support a high frequency, high data rate solution at high speed.

From the **business point of view**, narrowband SATCOM solutions could stand as a strong option for providing safety-critical applications for rail, especially if a future maturation of requirements should segregate or eliminate the need to support voice communications together with safety-critical data. In addition, SATCOM solutions can help to introduce ERTMS on those lines where, due to the high cost of terrestrial infrastructure, it is not deployed yet.

In comparison, for such a case, and assuming a *Brownfield* scenario (*i.e.* where a current GSM-R infrastructure is deployed) a modest implementation of LTE would prove competitive against SATCOM narrowband solutions with a slightly higher cost, provided a generous re-utilisation and upgradability for current GSM-R infrastructure was carried out. For a *Greenfield* scenario (*i.e.* on a deployment from scratch where there is no infrastructure to re-use), LTE losses its competitiveness regarding SATCOM solutions, since it is required a whole infrastructure deployment along the line(s) where to provide the service.

Meanwhile, broadband solutions offer the possibility of incorporating a source of revenue that, if leveraged wisely from a commercial point of view, could lead to profitability—resulting in a very high NPV in the long term. GEO/Ka-band offers a good competitive edge in economic terms in the same class as a moderately conservative LTE estimate.

In addition, the modularity and the OPEX-intensive economic model proposed by SATCOM solutions offer the possibility of a gradual implementation. In stark contrast, LTE implies that in general a small number of infrastructure managers should have to make strong initial investments to deploy terrestrial infrastructure, and with little room for a scaled deployment, requiring instead a comprehensive land-based infrastructure to provide initial operating capability. All this makes LTE a more financially-demanding solution compared with that of SATCOM broadband candidates.

As a result, SATCOM solutions can be implemented at a rather low and progressive initial investment in select rail services to fulfil the current demand, hence providing a solid platform to stand as either a stop-gap measure for more investment-demanding solutions, or as initial proof-of-concept and progressively ramped-up services for full-scale deployment in their own right.

### 11.2 GENERAL CONCLUSIONS AND RECOMMENDATIONS

Figure 91 shows the complete compliance matrix of technical, multi-technology and non-technical criteria for the eleven SATCOM systems evaluated. This matrix shows that all the SATCOM solutions assessed have more than one criterion not compliant plus some partial compliant, as well. It means that, **if SATCOM is considered the only mean of communications, there is not any SATCOM system fully compliant with current criteria identified**. This is mainly because GSM-R voice requirements become the main barrier for SATCOM, due principally to the fact that their values are out of the scope of any current SATCOM solution (in terms of availability, latency and even capacity for the whole European demand). Therefore, it is strongly recommended to reconsider such requirement's values (*i.e.* latency and availability) taking into account the **safety cases** for these scenarios where SATCOM could be working standalone (*e.g.* remote/rural areas).

It is worth mentioning that a similar situation have been considered in the **aeronautical environment**, where ATM (*Air Traffic Management*) applications requirements are classified according the **airspace domain**, such as the APT/TMA (*Airport/Terminal Manoeuvring Area*), ENR (En Route) and the ORP (Oceanic, Remote and Polar). For example, in the areas where SATCOM is the only mean of communications (*i.e.* ORP), QoS requirements (*e.g.* latency) are relaxed, and not only to make possible the use of SATCOM where no other terrestrial system is available, but also because the specific features of these domains (in terms of number of users, operations required, etc) make possible this relaxation keeping the safety case. For the contrary, in APT/TMA, it is mandatory the presence of, at least, two different links, *i.e.* multilink (LDACS/VDL2, AeroMACs).

Having a look of the complete compliance matrix in more detail, it can be observed that:

- All the solutions are compliant with the multi-technology criterion, meaning that all of them can be integrated within a FRMCS consisting of several communications systems (*i.e.* heterogeneous technologies) and allowing the convergence of networks that would enable a multi-link scenario.
- The system technically best evaluated (the MEO/C-band solution) is also the worst evaluated non-technically. It is because of the MEO/C-band is nowadays only a theoretical solution[19].
- The IRIS FOC solution has a similar behaviour than the MEO/C-band, since its technical evaluation is highly positive (only with a bad grade on the double-hop delay required in voice applications). In addition, this solution is currently planned, although from 2025.
- Some of the other systems best positioned, the GEO/C-band solution, has main problems on the double-hop delay, handhelds and security but, on the other hand, its non-technical evaluation is largely positive.

| Criterion ID | Satcom technology | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| | Iridium NEXT | MEO / C-band | Inmarsat 4 (BGAN) - Inmarsat 6 (ICE) | IRIS FOC | Thuraya | GEO / S-band | GEO / C-band | GEO / X-band | SmartLNB | GEO / Ku-band | Inmarsat 5 (Global Xpress) |
| CRT-TECH-1 | NC | C | NC | C (Low) | NC | C (Low) | C (Low) | NC | NC | NC | NC |
| CRT-TECH-2 | C (Low) | C (High) | C (Low) | C (High) | C (Low) | C (Low) | C (High) | C (High) | C (High) | C (High) | C (High) |
| CRT-TECH-3 | C | C | C | C | C | C | C | C | C | C | C |
| CRT-TECH-4a | C (High) | C (High) | NC | C (Low) | C (Low) | NC | C (Low) | C (Low) | NC | C (Low) | C (Low) |
| CRT-TECH-4b | C (High) | C (High) | NC | NC | NC | NC | NC | NC | NC | NC | NC |
| CRT-TECH-5 | C (High) | C (High) | C (Low) | C (Low) | C (Low) | C (Low) | C (Low) | C (Low) | C (Low) | C (Low) | C (Low) |
| CRT-TECH-6 | C | C | NC | C | C | C | C | C | C | C | NC |
| CRT-TECH-7 | NC | C | NC | C (High) | NC | C (High) | C | C | C (High) | C | C |
| CRT-TECH-8 | NC | C | PC | C | NC | C | C | C | C | C | C |
| CRT-TECH-9 | C | C | C | C | C | C | C | C | C | C | C |
| CRT-TECH-10 | C | C | C | C (Low) | C | PC | C | C | PC | C | C |
| CRT-TECH-11 | C | C | C | C (Low) | C (Low) | C (Low) | C | C | C | C (High) | C (High) |
| CRT-TECH-12 | NC | C | NC | C | NC | C | C | C | C | C | NC |
| CRT-TECH-13 | C | C | C | C | C | C | C | C | C | C | C |
| CRT-TECH-14 | C | C | C | C | NC | C | C | C | PC | C | C |
| CRT-TECH-15 | C (Low) | C (High) | C | C (Low) | C (Low) | C (Low) | C (High) | C (High) | C (Low) | C (High) | C (High) |
| CRT-TECH-16 | C (Low) | C (Low) | C (Low) | C (Low) | NC | C (Low) | C (High) | C | C (High) | C (High) | C (Low) |
| CRT-TECH-17 | C (Low) | C | C (Low) | PC | C (Low) | C | PC | PC | PC | PC | PC |
| CRT-TECH-18 | C (Low) | C (High) | C (High) | C (High) | C (Low) | C (High) | C (High) | C (High) | C (High) | C (High) | C (High) |
| CRT-TECH-19 | NC | NC | C | NC | NC | PC | NC | NC | PC | NC | NC |
| CRT-MULT-1 | C (Low) | C (High) | C (Low) | C | C (Low) | C | C (High) | C (High) | C | C (High) | C (High) |
| CRT-NONT-1 | PC | NC | C | NC | PC | PC | C | C | C | C | PC |
| CRT-NONT-2 | C | C | C | C | C | C | C | PC | PC | PC | PC |
| CRT-NONT-3 | C | NC | C | PC | C | C | C | C | C | C | C |
| CRT-NONT-4 | C | C | C | N/A | N/A | N/A | C | N/A | C | C | N/A |
| CRT-NONT-5 | C | C | C | N/A | N/A | N/A | C | N/A | C | C | N/A |
| CRT-NONT-6 | PC | C | PC | C | PC | PC | PC | PC | PC | PC | PC |
| CRT-NONT-7 | C | NC | PC | NC | C | C | C | C | C | C | C |

Figure 91: Complete compliance matrix

Figure 92 shows a comparison among the different SATCOM solutions analysed. The graph shows a "total score" computed taking into account the complete compliance matrix of Figure 91[20].

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[19] Despite the MEO/C-band is only a theoretical solution, a similar solution exists nowadays. It is a MEO/S-band (ICO), which is currently reaching its end of life.

[20] Results have been calculated assigning a score of 1 point to PC and 2 points to compliant evaluations.

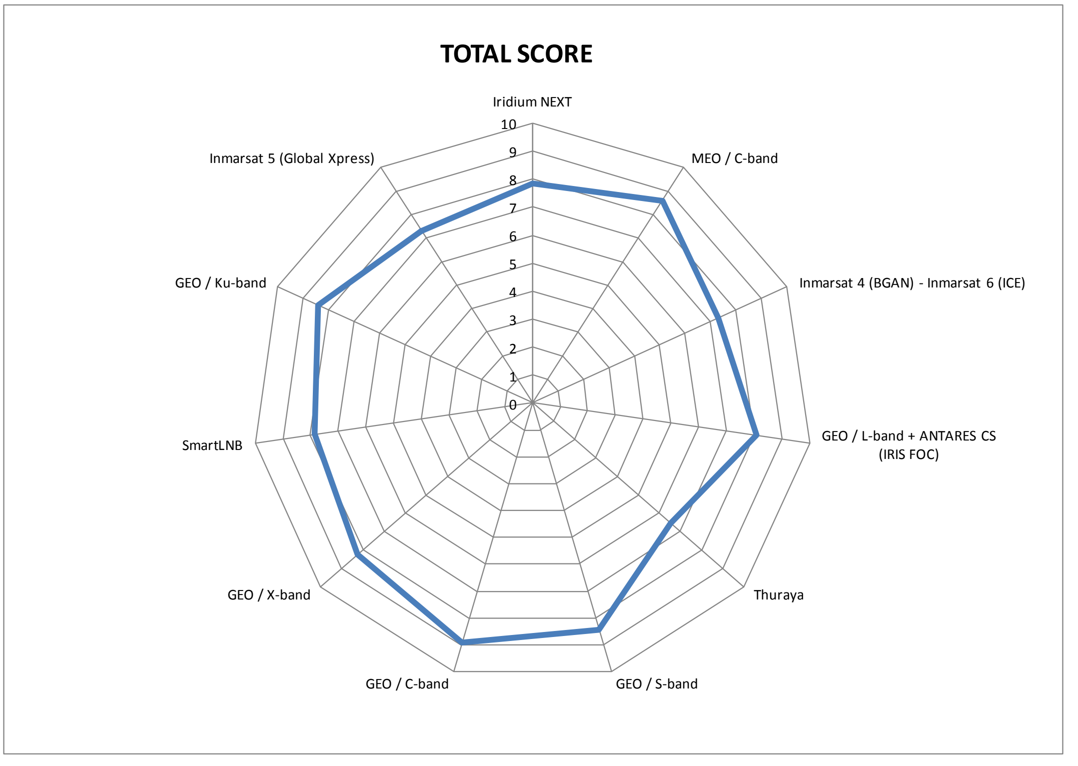


Figure 92: Total score of the SATCOM solutions analysed

Therefore, this Figure 92 gives at first sight an idea about the behaviour of the different SATCOM systems. For example, it can be observed that MEO/C- and GEO/C-band solutions are the ones with the maximum total score considering the whole set of criteria (technical, multi-technology and non-technical). Other solutions with a similar total score are the GEO/Ku- and GEO/X-band. On the contrary, Thuraya is the solution with the lowest score.

When making the same figure but considering only the **technical criteria** (see Figure 93), it can be observed that some solutions like GEO/Ku- or GEO/X-band do not compensate with the non-technical criteria and, in this case, they have a considerable worst score than mainly MEO/C-band, the best solution considering only technical criteria. The GEO/C-band keeps being the second solution after the MEO/C-band, but in this case clearly below the MEO/C.

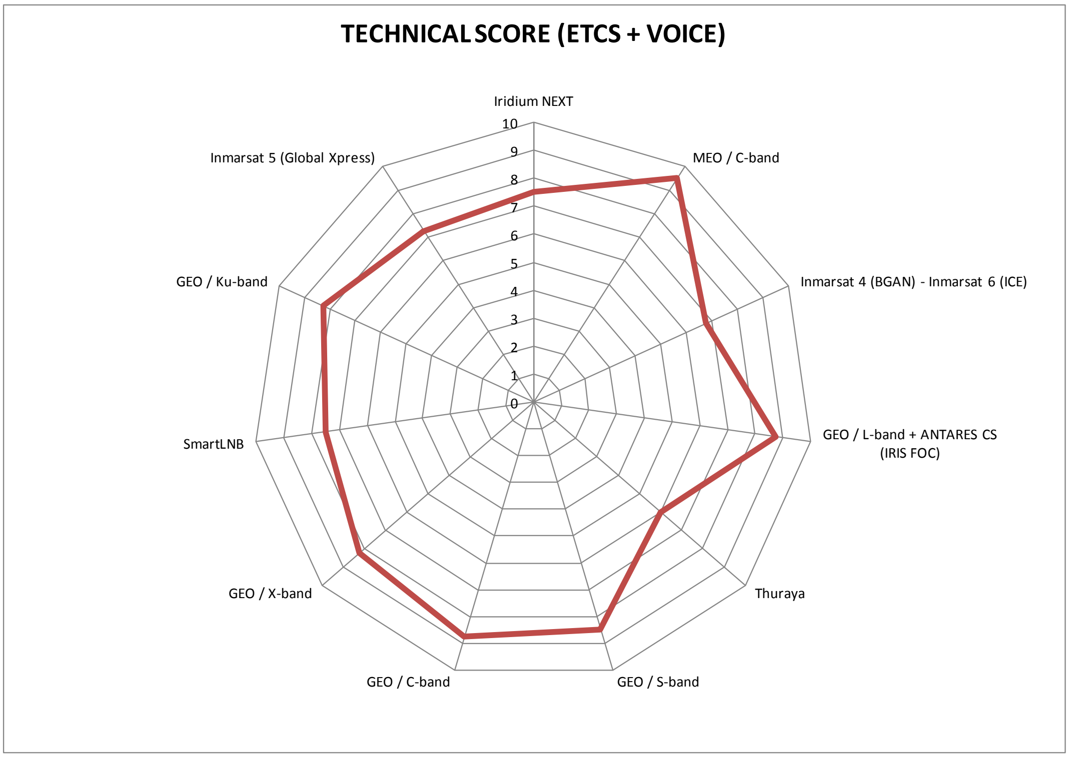


Figure 93: Technical score (ETCS + Voice applications) of the SATCOM solutions analysed

It is worth mentioning that technical evaluation has been performed considering both voice and data (ETCS) applications. It has also been stated that, if voice applications were not required, technical criteria that are more difficult to comply by SATCOM solutions could be achieved (such as the *link availability*) or even eliminated (such as the use of *handhelds*). In this case, and performing the same previous calculation but considering **only ETCS data** application, technical requirements could improve, as Figure 94 shows (take into account that this figure has a different scale in order to appreciate better differences among solutions). In this case, it can be observed that, in general, all the solutions improve a lot regarding the previous graph where both voice and ETCS data applications were considered. In fact, all the solutions seem to improve a similar value except for the MEO/C-band solution, whose improvement is lower because of this solution was already compliant with most of the technical criteria.

Hence, and considering the scenario with only ETCS data application, the hypothetical MEO/C-band and the IRIS FOC (GEO/L-band + ANTARES CS functionalities) are the best-scored solutions.

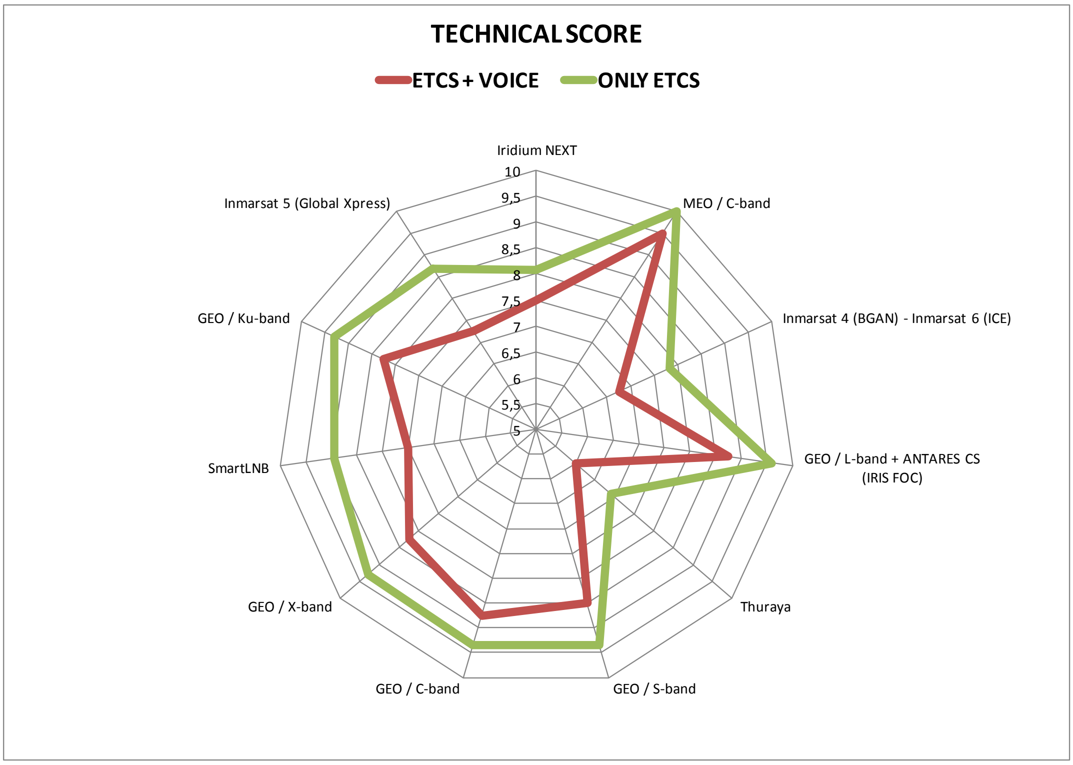


Figure 94: Technical score comparison considering “ETCS + Voice” and “Only ETCS” applications

Therefore, the main conclusions that can be drawn after the assessment of all criteria (see Figure 91 and Figure 92) are that:

- No SATCOM system being the only mean of communications is fully compliant with all the current criteria identified.
- Some of the best-positioned solutions (existing systems operating at lower frequency bands, such as GEO/S- or C-band) could be integrated within a FRMCS with some limitations in some of the applications to be provided.

Hence, and taking into account the possible limitations of best-positioned existing SATCOM solutions, the following **recommendations** are provided:

- Some scenarios are more propitious that others when it comes to deploying SATCOM on railways (just as it has been detailed in section §10 when talking about operational and deployment conditions). They are the ***High Speed Lines*** and ***Regional Lines***.
  Answers from the survey conducted in this study (see section §7) show that rail stakeholders have currently a similar idea about the scenarios where SATCOM could be important for railways, mainly for low density/regional lines.
- Despite the survey to rail stakeholders shows that voice services remain as a crucial requirement, it is very important to reconsider the type of applications that should be supported by a SATCOM

system, since they will limit the feasibility of the SATCOM solution. In this case, for example, if the **SATCOM system was just to provide ETCS data** (*i.e.* not considering voice services):

- Data rate would be limited, thus making it possible to provide higher availability.
- Handhelds (one of the main SATCOM limitations) would not be required anymore.
- Double-hop delays (not compliant with GEO SATCOM solutions) would not be considered anymore, since communications would take place between users (trains) and the SATCOM HUB (*i.e.* ground station).

- In (regional) lines with low traffic volumes and low-to-medium speed, it could be feasible to keep ETCS data and also voice services in exchange for relaxing some criteria (*i.e.* something similar to ERTMS regional). That would allow the use of ERTMS in those lines currently deprived of an automatic train protection and management system mainly due to economic deployment reasons.

Finally, and with the aim of clarifying some of the points detected at this study that need more analysis in order to provide a more accurate SATCOM solution for railways, or even developments or upgrades required for the SATCOM industry to provide products for railways, several recommendation for way forward are presented:

- To estimate accurately the **railway data traffic** demand by means of **simulations** considering both number and distribution of users, in order to be able to corroborate theoretical studies and feasibility of SATCOM solutions (mainly in terms of capacity).
- The SATCOM industry to **upgrade essential elements for SATCOM** solution in trains, such as the antenna.
- To advance in the ***smart routing*** element/functionality that will be able to perform smooth transitions between the different bearers available (including SATCOM).
- Finally, and due to the strong potential synergies and compliances detected between the aeronautical and railway domains, to analyse how the **IRIS FOC** system, which is the future SATCOM solution to provide *Air Traffic Management* applications, could be also used for the railway safety applications, although some modifications could be required.

## 12. ANSWERS TO TOR QUESTIONS

1) *Can unmodified (off the shelf) satcom services and products deliver solutions which can support*
    a. *voice and data applications for the following categories:*
        i. *as bearer for IP based ETCS level 2/3 data application*
        ii. *as bearer for IP based voice applications*

Current SATCOM services and products, as the only mean of communication, **cannot support simultaneously both voice and data** railway applications.

Voice and data applications and their demands to the communications systems are very different. For the railway domain in particular, voice services are much more demanding than the ETCS data application, since they require more bandwidth and even different types of terminals including handhelds (if pedestrian users are allowed).

Therefore, if only **IP ETCS level 2/3 data applications** are considered, the **throughput demand is minimal**, since a user (train) could send/receive one message every few seconds. This throughput reduction regarding voice applications helps to improve one of the most critical criteria for SATCOM, the **link availability**. In addition, only on-board terminals are considered for data applications, which means that the most demanding type of terminal in terms of SWAP (*Size, Weight and Power*), the handheld, is not required anymore since pedestrian users do not use ETCS data applications. Hence, and from the technical point of view, most of the SATCOM solutions analysed could provide the very narrowband demand of ETCS data applications. However, current solutions (unmodified) are not directly deployable in the railway domain because of the inexistence of SATCOM solutions certified and homologated by its use on trains for safety critical applications (such as the ETCS).

On the other hand, **IP based voice applications** add more constraints to SATCOM systems due to several causes:

- If pedestrian users are allowed, **handhelds** are required, and not all the SATCOM solutions can provide them.
- **Throughput** required by voice applications is much higher than the one required by data applications, implying more bandwidth that not all the systems can provide. In addition, the higher the throughput, the more difficult to achieve the required link availability.
- Most of the SATCOM systems require **double-hop** for voice calls between SATCOM terminals. The **delay** in this case discards GEO solutions.
- Voice applications for railways require special services currently only provided by GSM-R (and in a circuit-switched mode).

Therefore, from the technical point of view and even without considering certifications and homologations required for the railway domain, **current SATCOM solutions are not able to provide IP voice applications**, since the link availability and/or the delay criteria makes not possible the use of any of the analysed existing solutions.

Hance, current SATCOM solutions are only able technically to provide railway data services. It means that, if voice services were not required (for example in a hypothetical future situation where voice services were replaced by data services), or were required only on those areas where there are also deployed terrestrial systems capable to provide railway voice services (such as in train stations, where the deployment of terrestrial solutions is most feasible and where voice applications are more used), several SATCOM systems could be chosen as a part of the multi-technology future railway architecture (since more restrictive criteria disappear or are easier to be achieved due to new conditions).

*2) When not or only partially: can modified off the shelf services and products deliver solutions for the above mentioned categories?*

Currently, it does not exist a **regulatory framework** where SATCOM solutions could be certified and homologated for the railway domain. Therefore, solutions technically compliant with railway criteria shall be updated (if required) in order to comply with these future established regulations.

From the technical point of view, nowadays there exist SATCOM solutions compliant with **only data railway services** (*i.e.* ETCS level 2/3), such as the GEO L-, C-, X- or Ku-band solutions.

A different situation is contemplated for **voice services**, since most of the SATCOM solutions analysed are not able to provide them complying with the identified criteria. In fact, only the theoretical SATCOM solution analysed, the MEO/C-band, is able to provide **both voice and data** (ETCS) applications simultaneously. Nowadays there exists a similar solution based on a MEO/S-band system called ICO, but it has not been analysed because of its near end of life. Anyway, this current solution reveals that the MEO/C-band solution proposed is feasible from the technical point of view.

SATCOM voice services for railways also require the implementation of the whole set of railway voice applications, *i.e.* the ones that are currently in use in the GSM-R system plus the ones considered within the URS document (mainly those categorised as critical applications), such as voice communications between train and ground (controller), group calls, railway emergency communications, shunting voice communications, public emergency calls, etc. But this situation is exactly the same that for those future railway terrestrial IP communication systems, since currently only GSM-R is able to provide voice railway services, but in circuit-switched mode. This means that an implementation of IP voice services for railways shall be implemented regardless of the future IP communication systems (terrestrials and satellites).

Another important aspect to be considered mainly for voice services (since they are much more demanding that ETCS applications) is the bandwidth required to satisfy the railway European demand, since not all the SATCOM solutions are able to provide this demand and/or its geographical distribution. This point is of high importance and shall be studied in detail with probably the use of specific tools (such as traffic simulators) before the selection and/or design of the SATCOM solution for railways.

But in the future communication architecture for railways, which could be composed of terrestrial and satellite IP systems, some other modified off the shelf services and/or products need to be considered because of the multi-technology. A clear example of these new services or products is the *smart-router*, which will be capable of changing seamlessly of bearer (*i.e.* to execute vertical handovers and without disrupting the IP session established by the previous bearer) according to configuration and current bearer's availability.

Railway specific hard environment and the use of a multi-technology communication architecture could also require some additional modification(s) in the IP systems selected in order to adapt, for example, their physical layer to the so demanding railway channel or their interface with new elements because of the multi-technology. For instance, the physical channel could require the addition of special techniques in order to counteract main impairments due to the railway channel (such as the fast fadings caused by catenaries and power arches or the Doppler effect due to the high speed). And regarding multi-technology, if for example the IMS (IP Multimedia Subsystem) is used to control data flow policies and their QoS (Quality of Service) regardless of the transport network, specific signalling with the elements involved in the IMS platform should be implemented.

### *3) On what geographical part of the European railway network could a satcom solution be used successfully?*

The complete set of SATCOM solutions assessed provides coverage to the pan-European region, since solutions not compliant with this requirement have been discarded in advance (such as the O3b solution).

However, depending on the final SATCOM solution selected, not all the areas will be covered with the same quality, due mainly to the **satellite elevation angle**. In this sense, if the SATCOM solution is based on a geostationary (GEO) constellation, northern European areas will have lower satellite elevation angles than southern parts of Europe. It means that northern countries will have a degraded service regarding southern ones.

On the contrary, solutions using Low or Medium Earth Orbits (*i.e.* LEO or MEO) do not have this constraint, since satellites are continuously in movement and one new satellite *appears* when the current being used has reduced its elevation angle to the minimum required by design.

Other important aspect to be considered when talking about geography is the **distribution of users**, since for a SATCOM solution is not only relevant the total number of users to be served, but also how they are located. This is because, SATCOM, unlike terrestrial systems, do not require a specific deployment per each new line. This positive aspect of SATCOM solutions implies that the same system deployed and operative have to absorb new users when new lines are created or implemented with ERTMS. A clear example is a system with more than one satellite (such as LEO or MEO constellations), where the total capacity of the system is the capacity of a satellite multiplied by the number of satellites. But if all users are located in an area covered by only one satellite at one specific time interval, the system could not be able to absorb the total demand even though the complete system had enough capacity for that number of users (if they were located uniformly along the area covered by the system). Therefore, studies and simulations about traffic demand and its distribution are required in order to avoid service disruptions.

### *4) What are the conditions to create and implement suitable solutions?*

In order to successfully deploy a SATCOM solution as part of the multi-technology railway architecture, several aspects have to be considered, such as the *regulatory framework*, *railway certifications*, the use of *communication standards*, *geographical constraints* and some other *technical implications* as a result of introducing SATCOM technologies into the railway field and in a multi-technology architecture. It is even of relevance to consider the SATCOM *market interest* to offer products and services for the railway domain, since without this interest the previous aspects can hardly be achieved.

Currently, a **regulatory framework** for SATCOM in railways does not exist. It means that there is not a frequency band reserved for railway services, but it also means that no SATCOM equipment to be used for these applications are homologated by satellite operators. And it is valid for all the possible satellite frequencies (*i.e.* from L- to Ka-bands), regardless of whether the solution is a short-term or a long-term solution. It is not clear (yet) whether a range of frequencies have to be reserved or not to assure the requirements of the railway safety applications, since more studies are required in this sense (although it seems sensible in order to keep a stable band for safety applications). But in order to assure interoperability, it seems even more reasonable that at least a well defined frequency band where to operate shall be established. In addition, final equipment to be used for railways shall be homologated by satellite operators, in order to control, for example, the maximum permissible level of *off-axis*, which depends on the antenna design and is related with the interferences generated to other satellites because of the antenna directivity pattern used due to the mobile channel conditions in order to be able to guarantee the pointing.

Something similar occurs with **railway certifications**, since there are currently few SATCOM equipment providing railway certifications (*i.e.* based on EN50155 rules and its derivatives). This aspect is directly related with the **market interest**, since the higher the interest, the higher the number if equipment available for railways. According to the survey conducted throughout this study, SATCOM industry is interested in railways and, despite currently there are few SATCOM equipment certified for railway domain, the perception is that current SOTM products are suitable for this domain. This market interest from satellite industry should be complemented with awareness and also interest from the railway domain, which, according to the survey, currently consider unanimously that SATCOM cannot be the single, main solution for the future railway communications system. However, they mostly agree on the possibility that SATCOM may play an important role as part of it, either as a complementary system for some scenarios, a backup system, or a backhaul.

The use of **communication standards** is also of high importance, since this feature allows many manufacturers to provide competitive solutions. Some of the main SATCOM standards includes annexes about how to implement SOTM (SATCOM On The Move) solutions, and even how to implement commercial SATCOM solutions for the railway domain are introduced on these annexes (such as for example in the DVB-RCS+M standard). But SATCOM standards do not refer about how to provide safety critical applications for railways. Therefore, some adaptations for the use of standards with these safety critical applications could be required (mainly oriented to overcome impairments of the unfavourable railway channel).

Satellite communications require line-of-sight. Since this is a very demanding feature difficult to assure along a railway line because of **geographical constraints** (such as tunnels, buildings, mountains, etc.), terrestrial solutions are required to mitigate this effect. In this sense, the use of **gap fillers** (gateways that transform satellite signal to terrestrial and vice-versa) and/or deployments of **terrestrial systems** are necessary. The use of gap fillers or terrestrial solutions will depend, at the end, on the area to be covered. For example, urban areas with lots of users are expected to be covered by terrestrial systems, since their deployments are feasible. On the contrary, rural areas with a small number of users are expected to be covered by gap fillers, since deployment of terrestrial systems in these locations could be too much expensive and difficult.

Finally, due to the introduction of SATCOM into a new market, new **technical challenges** (or **technical implications**) arise. In this case, the use of SATCOM in railways implies the adaptation of satellite communications equipment to railway scenarios and regulations. The main technical implication is the use of a satellite antenna into the roof of the train, which depending on the final solution chosen, it could be small and omnidirectional (cheap and easy to install and maintain) or larger and directive (expensive and more difficult to maintain). Anyway, final design of the antenna and the other equipment shall comply with current railway and SATCOM regulations.

Since SATCOM (if finally used in railways) will be only one of the different technologies of the future railway communications architecture, it will have to be integrated within a **multi-technology scenario**, allowing the user to change of communications system according to its status, configuration and network availability. In this future architecture, it is expected to have services and applications independents of bearers, as the Next Generation Networks (NGN) tend. Several new elements or services will arise, such a *smart router* capable to execute vertical handovers, or even new services capable to keep connections and their quality of service (QoS) regardless of the transport network used, as the IP Multimedia Subsystem (IMS) does. These new elements, because of the multi-technology scenario, will have to be integrated with all the future railway communications systems (terrestrials and satellites).

*5) What could be the economic impact (cost savings) of satcom solutions compared with full terrestrial solutions?*

The answer is strongly dependent on three key factors:

1. **The choice for narrowband vs. broadband solutions**: There are currently both terrestrial and SATCOM COTS solutions available in both categories, despite the technical and functional shortcomings affecting a number of them for use in rail communications. A broadband solution would require a costlier deployment, although it would enable on-board value added services to be provided by railway undertakings via the same platform as current safety-critical functionalities. On the contrary, a narrowband solution would typically ensure lower lifecycle costs at the expense of this capability.
2. **The inclusion of voice communications**: If the mandate for this capability, currently supported by GSM-R, were to be relaxed or repealed, it would trigger a two-fold impact. First, it would eliminate the need for handheld terminals, which are costly (compared to terrestrials ones) and are not supported by some SATCOM solutions. And second, it would significantly reduce the data rate requirement and therefore, the operating expenses tied to any solution.
3. **The uncertain deployment requirements for broadband terrestrial technologies to provide high data rates at speed**: Despite multiple studies and a number of trials on this subject, findings have so far failed to point at an uncontested conclusion. It has been suggested that, while current narrowband GSM-R base stations could be upgraded to provide broadband LTE services, the needs to shift to a higher frequency and to guarantee a higher data rate would require anywhere from twice to four times the number of stations in order to reduce the distance between them and be able to provide the required service.
   Therefore, one to three new-build such stations should be deployed between any pair of existing upgraded GSM-R ones. On the contrary, broadband SATCOM solutions are immune

to this weakness thanks to the distance of orbiting satellites, compared to the proximity of ground stations to fast-moving train sets.

Based on the above factors, if a narrowband solution was eyed as a direct replacement of current GSM-R capabilities, up to four existing and proposed SATCOM solutions could provide a full lifecycle cost-saving ranging from 4.200 to 6.200 M€ over 20 years in the EU-28 + Norway + Switzerland region, compared to keeping GSM-R or implementing GPRS. The same solutions would also outperform a typical upgrade of existing GSM-R stations to LTE-standard, from a business standpoint, by 3.600 to 5.600 M€ in the same time and geographic scope.

This economic advantage would potentially increase if voice ceased to be a requirement, something that would also alleviate the technical and functional shortcomings of existing SATCOM solutions, making for a stronger global value proposition.

On the contrary, if a broadband solution was adopted, this should be on the grounds that railway undertakings could use the same communications platform to provide on-board value added services to passengers. In turn, this could generate an additional revenue stream valued at over 2.800 M€ every year in the EU-28 + Norway + Switzerland region. In the case of broadband SATCOM solutions, this revenue would compensate for their higher lifecycle cost, producing a positive global business case worth 24.000 to 29.000 M€ compared to GSM-R lifecycle costs over the same 20 years.

The comparison of the above SATCOM broadband solutions to their terrestrial peer, i.e. LTE, is dependent, as mentioned before, on the latter's need for additional base stations to guarantee high frequency and high data rate communications at speed. SATCOM would provide a stronger business case than LTE if the current deployment of GSM-R base stations were required to triple or higher. If the requirement was to only double deployment or leave it unaltered (besides technology upgrades in existing stations), the business case for broadband SATCOM solutions would be weaker than LTE's.

# ANNEXES

## A. CRITERIA DEFINITION

This section defines the list of applicable criteria for the subsequent assessment of satellite communication systems and/or related technologies regarding their feasibility to support the critical railway applications. To reach this goal, each criteria is accompanied of a rationale or justification and also its traceability to the reference documentation. Table 40 summarizes the information provided for each criterion.

| | |
|---|---|
| ***Criterion*** | Definition of the evaluation rule to be followed during the evaluation phase. |
| ***Rationale*** | Justification of the selected criterion. |
| ***Criterion Traceability*** | Documentation (requirement, specification, etc) on which is based the selected criterion. |

Table 40: Definition of traceability matrix fields

Several sources have been considered when identifying and justifying the different criteria. Recent documentation from the FRMCS project (mainly the URS document) is one of the main inputs, since the independence of the applications from the bearer are a must for the study of the satcom feasibility for railway communications.

However, the lack of details of the URS document (it does not include full detailed requirements yet) has caused (for some specific criterions) the use of current GSM-R documentation in order to has some first reference values when required or considered of relevance.

Therefore, main sources used and traced for the criteria identification:

- FRMCS URS v2.0
- EIRENE SRS & FRS
- Different Subsets
- ITU-T documentation
- etc

Some comments and assumptions have been considered while defining main satcom criteria:

- It is worth to mention that current QoS and performance parameters have very demanding criteria because they refer to high-speed railway lines. Therefore, they could be relaxed in case of regional or low traffic lines.
- For the criterion identification, it has been considered several guidance[21] defined within the URS document [AD-01], which indicate that future railway communication system shall keep current performance and quality of communication provided by GSM-R or public services. Therefore, the future railway communication system is expected to comply at least with current GSM-R

[21] Guidance **GN4**: "*Capacity, reliability, availability, maintainability, quality of service are characteristics to be used to meet the operational needs of the railways. The "End to End" performance shall be equal-to or better-than legacy radio systems, for example GSM-R*".

Guidance **GN5**: "*The user expects a quality of communication (integrity, clarity, accuracy etc.) which is considered to be normal for the users by being equal to or better than what can be expected from a public service, and is sufficient to perform the railway operation*".

requirements. For that reason, and due to the lack of detail in the definition of the user requirements for the FRMCS, current GSM-R requirements are still sometimes considered as a reference.

- Table 41 (extracted from "*Subset-093 – GSM-R Interfaces Class 1 Requirements*") summarises main GSM-R QoS requirements. Since GSM-R is a Circuit Switch (CS) based system, some of these main QoS requirements could not match with the ones taken into account for a baseline Packet Switch (PS) system (e.g. IP based network).

| QoS Parameter | Value |
|---|---|
| Connection establishment delay of mobile originated calls | <8.5s (95%), ≤10s (100%) |
| Connection establishment error ratio | $<10^{-2}$ |
| Maximum end-to-end transfer delay (of 30 byte data block) | ≤0.5s (99%) |
| Connection loss rate | $\leq 10^{-2}$ /h |
| Network registration delay | ≤30s (95%), ≤35s (99%), ≤40s (100%) |

Table 41: Summary of GSM-R QoS requirements ("*Subset-093 – GSM-R Interfaces Class 1 Requirements*")

## A.1 TECHNICAL CRITERIA DEFINITION

**CRT-TECH-1** The "link availability" of the proposed satcom system shall be **High**.

***RATIONALE***

The link availability of a communication system is directly related (and directly proportional) to the critical nature of the service provided. Therefore, the more critical service the higher link availability required. In addition, according to the URS document [AD-01], future railway communications shall be unaffected by environment or climatic conditions (refer to GN7). This requirement is very stringent and implies very high link availability.

Considering current GSM-R values as a first reference [RD-14], Table 42 shows link availability values that are assumed for the characterization of a Satcom system:

| | |
|---|---|
| **High** | Link Availability > 99.99% |
| **Medium** | Link Availability > 99% |
| **Low** | Link Availability < 99% |

Table 42: link availability values

***CRITERION TRACEABILITY***

- FRMCS URS v2.0 (GN7)
- EEIG 96S126 / 02S1266 (2.2.2.1.2): "*The ERTMS/ETCS quantifiable contribution to operational availability, due to hardware failures and transmission errors, shall be not less than **0.99984***".

- EEIG 96S126 / 02S1266 (2.3.2.2): "*The ERTMS/ETCS quantifiable contribution to operational availability, due to transmission errors, shall be not less than **0.999984***".

**CRT-TECH-2** The "reliability" of the proposed satcom system shall be **High**.

***RATIONALE***

Communications systems reliability is a key parameter that defines the dependability of the system. This parameter is usually expressed as a percentage of the average year, and its required value is related with the critical nature of the service. Therefore, the more critical service the higher reliability required.
As an example, following table summarizes MTBF and MTTRS parameters for GSM-R on-board equipment (see [RD-14]). These values are considered as **High** reliability.

| ON BOARD EQUIPMENT | Immobilizing Failures | Service Failures | Minor Failures |
|---|---|---|---|
| MTBF (on-board equipment | $2.7 \cdot 10^{6}$ hours | $3.0 \cdot 10^{5}$ hours | $8.0 \cdot 10^{3}$ hours |
| MTTRS | 1.737 hours | | |

Table 43: MTBF and MTTRS values for GSM-R on-board equipments

**Note:** System availability is computed by means of element's reliability and link availability, taking into account the redundancy of the elements and/or links and their management method.

***CRITERION TRACEABILITY***

- FRMCS URS v2.0
- EEIG 96S126 / 02S1266 v6

**CRT-TECH-3** The end-to-end error ratio of the proposed satcom system shall be **Low**. *Note*: Since this criterion only considers the satellite system, the error ratio shall be measured after the last satellite communication layer (e.g. data link layer or L2)

***RATIONALE***

The error ratio required of a system is given by final applications and its operational requirements. Current URS document [AD-01] does not specify this parameter, but considering that FRMCS shall support safety critical applications, the error ratio (BER, PER) will be low.

Some examples of current GSM-R requirements that talk about some error ratios, although not with the same approach:

- ***UNISIG SUBSET-93 v2.3.0 – 6.3.3.6***: "*The connection establishment error ratio of mobile originated calls shall be <10-2 for each attempt"*.
- ***UNISIG SUBSET-93 v2.3.0 – 6.3.6.5***: "*The error-free period shall be >20s (95%), >7s (99%)*"

Table 44 shows also some examples of QoS requirements regarding tolerance to information losses depending on the service type [see RD-13]. These are the values considered for a **low** error ratio.

| | |
|---|---|
| **Conversational services (video and audio)** | PLR < 1-3% (BER < $10^{-3}$) |
| **Data (telemetry, C2, Telnet, etc)** | Error-free (PLR < 0,1%, BER < $10^{-8}$) |
| **Fax** | BER < $10^{-6}$ |

Table 44: Examples of QoS requirements for tolerance to information losses

***CRITERION TRACEABILITY***

- FRMCS URS v2.0
- UNISIG SUBSET-93 v2.3.0 (6.3.3.6; 6.3.6.5)
- ITU-T Recommendation G.1010: "End-user multimedia QoS categories"

**CRT-TECH-4** Transfer delay for the proposed satellite system shall be **Low**.

*Note*: It refers to the end-to-end (one-way) delay due to the satellite channel. Therefore, it shall be measured from satellite transmitter to satellite receiver.

***RATIONALE***

URS document [AD-01] defines several grades of "latency" according to the different applications described. The strictest one is "Low", which means "immediate".

For a satcom system the transfer delay will depend on the constellation type and bandwidth (data rate), and due to the distance from remote terminals to satellites this delay is usually greater than in terrestrial systems.

Following values (the most stringent part derived from GSM-R [RD-15]) are considered for the characterization of a Satcom system:

| | |
|---|---|
| **Low** | Transfer delay < 0.5 s |
| **Medium** | 2s < Transfer delay > 0.5 s |
| **High** | Transfer delay > 2 s |

Table 45: Transfer delay values

***CRITERION TRACEABILITY***

- FRMCS URS v2.0
- UNISIG SUBSET-93 v2.3.0 (6.3.4.3): "*The end-to-end transfer delay of a user data block of 30 bytes shall be ≤0.5s (99%).*"

**CRT-TECH-5** Delay jitter of the proposed satcom system shall be **Low**.

*Note*: Since this criterion refers to the one-way satellite channel jitter, it shall be measured from satellite transmitter to satellite receiver.

***RATIONALE***

Since some of the railway critical applications are voice services, delay jitter of the satellite system for railways shall be small because excessive jitter makes speech choppy and difficult to understand.

To get high quality voice, the inter-arrival time of successive packets should be very similar to the inter-packets time at the transmitter side.

According to [RD-13] regarding end-users multimedia QoS categories, following values are assumed for the characterization of a Satcom system:

| | |
|---|---|
| **Low** | Delay jitter < 1 ms |
| **Normal** | Delay jitter > 1 ms |

Table 46: Delay jitter values

***CRITERION TRACEABILITY***

- ITU-T Recommendation G.1010: "End-user multimedia QoS categories"

**CRT-TECH-6** Network registration delay for the proposed satcom system shall be **Normal** (with similar values of current GSM-R system).

***RATIONALE***

The allowed network registration delay parameter is directly related with users applications requirements. Current URS document [AD-01] does not specify this value. Therefore and as a reference, current GSM-R values can be considered.

Reference values taken from GSM-R for network registration [RD-15]:

| | 95% | 99% | 100% |
|---|---|---|---|
| **Network registration delay** | ≤ 30s | ≤ 35s | ≤ 40s |

Table 47: Current GSM-R network registration delay

Therefore, following values (Table 48) derived directly from Table 47 can be considered for the characterization of this criteria (as a first reference):

| | |
|---|---|
| **Low** | Network registration delay < 35 s |
| **Normal** | Network registration delay > 35 s |

Table 48: Satcom system network establishment delay categorization

***CRITERION TRACEABILITY***

- FRMCS URS v2.0
- UNISIG SUBSET-93 v2.3.0 – 6.3.7.2: "*The GSM-R network registration delay shall be ≤30s (95%), ≤35s (99%).*"
- UNISIG SUBSET-93 v2.3.0 – 6.3.7.3: "*GSM-R network registration delays > 40 s are evaluated as registration errors*"

**CRT-TECH-7** The call establishment delay for the proposed satcom system calls shall be **Low**. *Note*: as a first reference, GSM-R establishment delays can be considered.

***RATIONALE***

The allowed call establishment delay is directly related with users applications requirements. The URS document [AD-01] does not specify this value, but it indicates that:

- FRMCS shall provide service to emergency calls
- Quality of communication of FRMCS shall be equal or better than current one.

Therefore, considering GSM-R values defined at EIRENE FRS 8.0.0 as a first reference (see Table 50), following values for the call establishment delay criteria (Table 49) is taken into account for the categorization of the satcom system:

| | |
|---|---|
| **Low** | Call establishment delay < 5 s |
| **Normal** | Call establishment delay > 5 s |

Table 49: Satcom system call establishment delay categorization

| | 95% | 99% |
|---|---|---|
| **Railway emergency calls** | < 4s | < 6s |
| **High priority group calls** | < 5s | < 7.5s |
| **All operational and high priority mobile-to-fixed calls not covered by the above** | < 7s | < 10.5s |
| **All operational and high priority fixed-to-mobile calls not covered by the above** | < 7s | < 10.5s |
| **All operational mobile-to-mobile calls not covered by the above** | < 10s | < 15s |
| **All other calls** | < 10s | < 15s |

Table 50: Current GSM-R call establishment delay

***CRITERION TRACEABILITY***

- FRMCS URS v2.0
- EIRENE FRS 8.0.0 - 3.4.1i: "*The requirements for end-to-end call set-up performance are indicated in following table*" (see Table 50).
- EIRENE FRS 8.0.0 - 3.4.2: "*The required call set-up times shall be achieved in 95% of cases.*"
- EIRENE FRS 8.0.0 - 3.4.3: "*Call set-up times for 99% of cases shall not be more than 1.5 times the required call set-up time*".

**CRT-TECH-8** The proposed satcom system shall allow (at least) the estimated number of European FRMCS users by 2030 registered simultaneously.

***RATIONALE***

According to iDate Annex document on the evolution of GSM-R [RD-12], the number of GSM-R terminals is probably under 100,000. It does not mean that all of them are working simultaneously, but it is the worst case.

For the future railway mobile communication system, and considering the increase showed by ERTMS statistics keeps the same evolution than between 2010 and 2014 (show image below from www.ertms.net) in the near future, we can assume that this number could duplicate (or even triplicate) the current number by 2030.

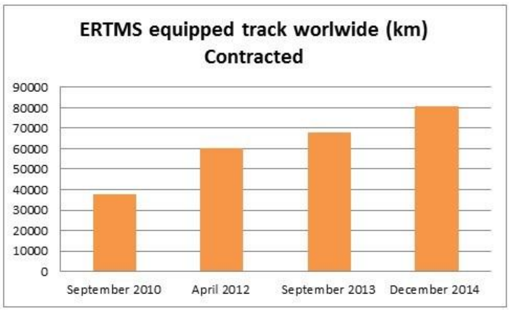


Figure 95: ERTMS equipped track worldwide (km) contracted

It is worth mentioning that this criterion is directly related with the capacity of the satcom system, but also with its scalability, which defines the ability of the system to manage demand variations.

***CRITERION TRACEABILITY***

- www.ertms.net
- iDate study [RD-12]

**CRT-TECH-9** The proposed satcom system shall provide **priority** and **pre-emption** mechanisms.

***RATIONALE***

The URS document [AD-01] defines ***Prioritisation*** as a *Critical Support Application*. This means that the railway communication system shall allow the use of precedence and pre-emption when required.

***CRITERION TRACEABILITY***

- FRMCS URS v2.0 (8.8)

**CRT-TECH-10** The proposed satcom system shall support **Data** and **Voice** services.

***RATIONALE***

The URS document [AD-01] specifies a set of technology independent user requirements for the FRMCS and in the form of individual applications. And these applications (critical and not critical) are based on data and voice services.

***CRITERION TRACEABILITY***

- FRMCS URS v2.0

**CRT-TECH-11** The proposed satcom system shall support as minimum Low bandwidth applications

***RATIONALE***

A narrowband communication system (like GSM-R) is able to provide the critical voice and data (ETCS) railway applications. The FRMCS URS v2.0 document details *Critical Communication Applications* (among the rest of foreseen applications catalogued as non critical), and all of these critical applications are detailed as "Low" bandwidth required.

However, the URS document also shows the great variety of applications (not only critical) that the future railway communications system should support, some of them requiring "medium" or even "high" bandwidth.

Therefore, and despite a narrowband system should be enough to provide service for critical applications, it is recommended a broadband communication system for supporting the whole set of applications defined at the URS document.

***CRITERION TRACEABILITY***

- FRMCS URS v2.0
- EIRENE SRS 16.0.0
- EIRENE FRS 8.0.0

**CRT-TECH-12** The proposed satcom system for the FRMCS shall provide "*user-to-user*" and "*multi-user*" types of communications for both voice and data services. In addition, each communication can be bi-directional or uni-directional with any type of asymmetry between forward and return channels (when bi-directional).

***RATIONALE***

According to the communication attributes defined in URS document [AD-01], the "distribution" of voice and data applications can be:

- User-to-User
- Multi-User

And the type of communication:

- Bi-directional
- Uni-directional

Within the URS document there are *critical communication applications* defined with every possible combination of *distribution* and *type* communication attributes.

***CRITERION TRACEABILITY***

- FRMCS URS v2.0

**CRT-TECH-13** The minimum required coverage of the satcom system shall be **Europe**.

***RATIONALE***

Since the ERTMS/ETCS is a European ATC standard for railway interoperability, the European area shall be covered (or possible to be covered) by the future railway communication(s) system(s) deployed.

In addition, those areas where currently it has been deployed also the ERTMS system (outside Europe), it should be possible to deploy the future communication solution.

Therefore, and as a recommendation, it is interesting to assure a future deployment of the selected communication architecture around the world.

***CRITERION TRACEABILITY***

- Interoperability Directive and TSIs
- FRMCS URS v2.0

**CRT-TECH-14** The satcom system shall provide communications for remote terminals when stationary and when travelling at speeds up to the maximum allowable line speed or 500 km/h, whichever is the lower.

***RATIONALE***

According to **URS** document [AD-01], the following definition for the "Speed" attribute is provided:

- Low <40 Km/h, including stationary users
- Normal >40 Km/h, <250 Km/h
- High >250 Km/h

Most of the critical communication applications defined within the same document require "High" speed.

In addition, following GSM-R rules are also considered as a reference:

- **EIRENE FRS 3.2.4**: "*The land-based part of the system shall provide communications for mobiles when stationary and when travelling at speeds up to the maximum allowable line speed or 500 km/h, whichever is the lower. (MI)*".
- **EIRENE FRS 4.1.4**: "*Mobile equipment operated in frequency band listed in clause 4.1.3i, 4.1.3ii and 4.1.3iii shall function as specified when travelling at speeds from 0 km/h to 500 km/h. (MI)*".

***CRITERION TRACEABILITY***

- FRMCS URS v2.0
- EIRENE FRS v8.0.0 (3.2.4 (*network*); 4.1.4 (*UT*))

**CRT-TECH-15** The proposed satcom system shall be flexible to support (at least) new created apps in the future.

***RATIONALE***

Since one of key points of FRMCS is the independence between bearer(s) and applications, the future communication architecture for railways shall be flexible enough to support future improvements, such as the addition of new applications.

***CRITERION TRACEABILITY***

- FRMCS URS v2.0 (Pr1 - GN14): *"The system shall be flexible to support new created apps in the future".*

**CRT-TECH-16** The proposed satcom system shall be highly and easily scalable.

***RATIONALE***

Taking into account current increase of number of GSM-R equipments in use worldwide (see following figure from www.ertms.net), the FRMCS shall foresee this fact and be based on communication systems easily scalable.

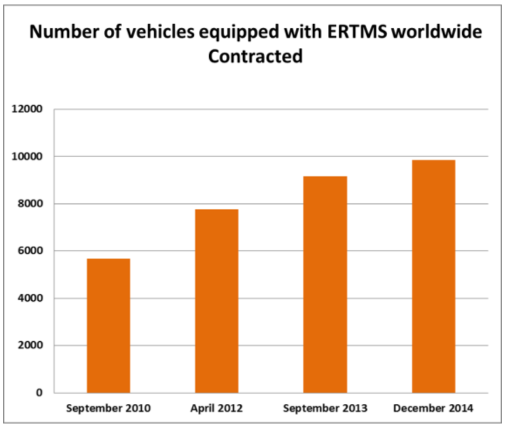


Figure 96: Number of vehicles equipped with ERTMS worldwide contracted

***CRITERION TRACEABILITY***

- FRMCS URS v2.0 (Pr1 – GN2)
- www.ertms.net

**CRT-TECH-17** The proposed satcom system shall allow the use of the following types of terminals: "*On-board (mobile)*", "*Handheld*" and "*Fixed*".

***RATIONALE***

Future railway communication system shall provide with the same type of terminals that currently are in use. Existing terminals can be categorized as follows:

| | |
|---|---|
| **On-board** | - Cab radio<br>- ETCS Data Only Radio (EDOR) |
| **Handhelds** | - General purpose radio (GPR)<br>- Operational radio (OR)<br>- Shunting radio (SR) |
| **Fixed terminals** | - Voice terminals<br>- Data radio terminals |

Table 51: Types of terminals and their categorization

Within a same terminal category, the different equipments can include more or less functionalities and/or features, but from the (satcom) bearer point of view, the three different categories (on-board, handhelds and fixed terminals) shall be supported.

***CRITERION TRACEABILITY***

- EIRENE SRS 16.0.0
- EIRENE FRS 8.0.0

**CRT-TECH-18** The proposed satcom system shall provide high level of safety in the information exchanged.

***RATIONALE***

High levels of safety will be required in the Future Railway Communication System in terms of **integrity** from protection **against non-intentional** (i.e. jamming) **interferences** point of view. Safety is interpreted as the integrity level of the message reached by mean of countermeasures implemented on the waveform (i.e. physical and link layer) to provide robustness in front of non-intentional interferences and/or channel impairments.

***CRITERION TRACEABILITY***

- EN 50126 RAMS – (S)afety
- EN 50129 THR/SIL per application in terms of integrity
- EN 50159
- EEIG 96S126 / 02S126
- UNISIG SUBSET-091
- UNISIG SUBSET-037
- UNISIG SUBSET-088

**CRT-TECH-19** The proposed satcom system shall provide high level of security in the information exchanged.

***RATIONALE***

High levels of security will be required in the Future Railway Communication System in terms of **integrity** from protection **against** malicious users or **intentional interferences** point of view. Security is interpreted as the integrity level of the message reached by mean of countermeasures implemented on the waveform (i.e. physical and link layer) to provide robustness in front of intentional interferences and/or jamming.

***CRITERION TRACEABILITY***

- EN 50126 RAMS – (S)afety
- EN 50129 THR/SIL per application in terms of integrity
- EN 50159
- EEIG 96S126 / 02S126
- UNISIG SUBSET-091
- UNISIG SUBSET-037
- UNISIG SUBSET-088

## A.2 TECHNICAL CRITERIA DEFINITION

This section defines criteria applicable for the complete communications architecture (including terrestrial and satellite systems) for the FRMCS. Just like with the baseline satcom system section, each criterion is complemented with a rationale or justification, and with a criterion traceability to the reference documentation (if required).

**CRT-MULT-1** All communication networks (e.g. satcom and terrestrial) of the future railway communications architecture shall be packet-switched (PS), since all the applications supported shall be IP based.

***RATIONALE***

According to network trends, the Next Generation Network (NGN) is packet based and uses IP to transport every traffic type (signaling, data, voice and video). It means that all services of future communication systems are going to be accessed by IP.

In addition, NGN concept separates applications from transport networks (bearers). This way, from the application point of view it will not be important the selected bearer. Figure 97 shows this new concept where several bearers are available and they are used depending on the type of terminal and availability. The core transport network is based on IP and the services and applications are agnostic to the bearer.

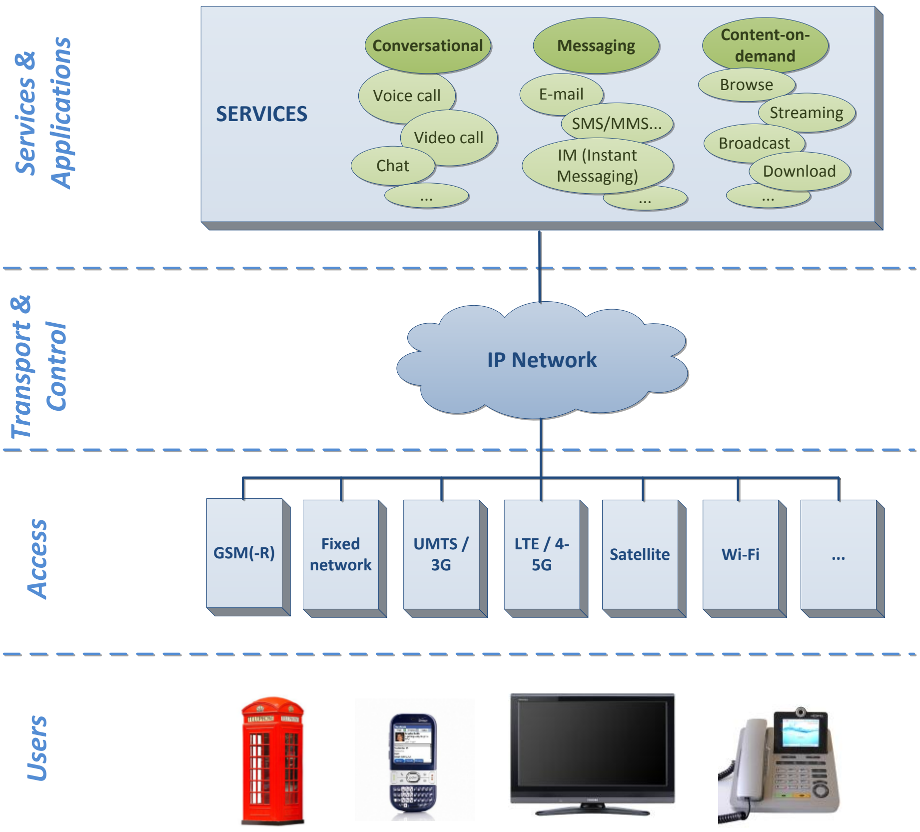


Figure 97: NGN convergence

Figure 98 shows the NGN architecture defined by the ITU-T (recommendation Y.2012) [RD-16]. It can be seen that applications are independent from the network and they are on the top of the architecture. (Generic) Interfaces between elements are standardized to guarantee integration between them (ANI (*Application-Network Interface*), UNI (*User-Network Interface*) and NNI (*Network-Network Interface*)).

The NGN architecture clearly separates the transport layer (also known as *Transport Stratum*), which includes both the access network and the core transport network, and the service layer (also known as *Service Stratum*), which is in charge of processing the signaling generated by the users when asking for a service.

At the core of the NGN architecture (within the *Service Stratum*) is the IMS (IP Multimedia Subsystem), which provides, for multimedia services, an independent access platform for a variety of access technologies, such as satellite, 3G, 4G, WiFi, cable… guaranteeing the end-to-end QoS according to user's SLA.

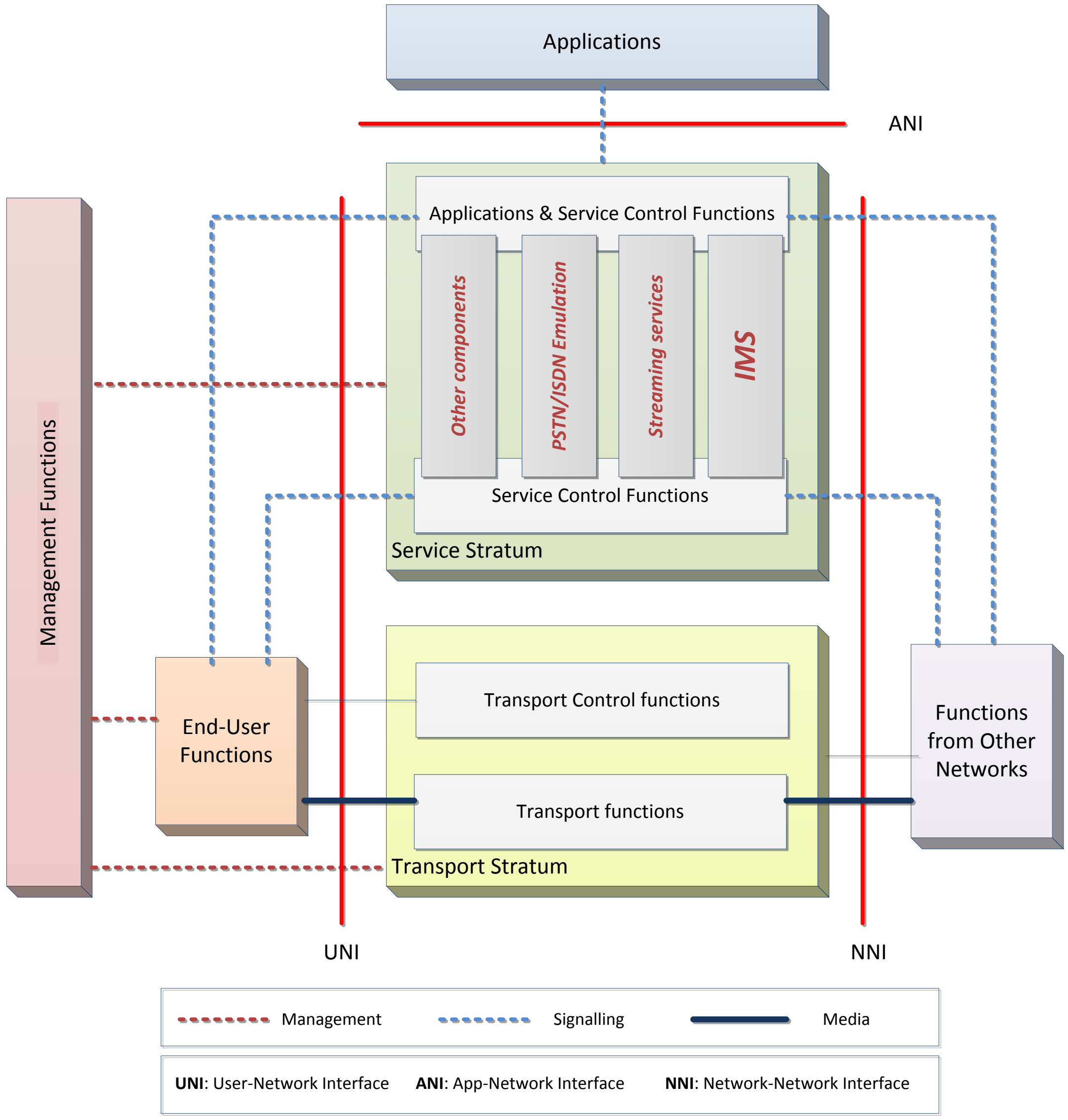


Figure 98: NGN architecture

## CRITERION TRACEABILITY

- FRMCS URS v2.0 (Pr1 - GN14)

- ETSI (recommendation Y.2012)

**CRT-MULT-2** The end-to-end QoS of a communication call/session shall be guaranteed according to user's SLA.

***RATIONALE***

One of the main NGN features is the separation between service and transport layers. It allows the service layer to reserve the required resources for every user information exchange (voice and/or data) independently of the bearer before starting the transaction. And these resources are kept (and adapted if required) until the end of the communication. This is a key difference regarding OTT (Over The Top) applications, which do not guarantee any type of QoS.

***CRITERION TRACEABILITY***

- ETSI

**CRT-MULT-3** Handovers among systems (also known as vertical handovers) shall be transparent to users (i.e. seamless).
Note: This means that during a (voice or data) communication, if a change of communication system occurs, the communication shall continue without any disruption and additional user's action.

***RATIONALE***

The FRMCS, just like an NGN, can be made up by a several communications systems (bearers). It means that, depending on the concrete situation of each user, a terminal may need to change of bearer in order to keep its connectivity. With the aim of not disrupting the service, a smooth transition between bearers is expected, and it shall be transparent, seamless and without any action required from the user side.

One important key element/mechanism within this point is the ***smart-routing***, which will provide the ability of changing of communication system when required according to current availability and some other possible information like the preferred network configuration.

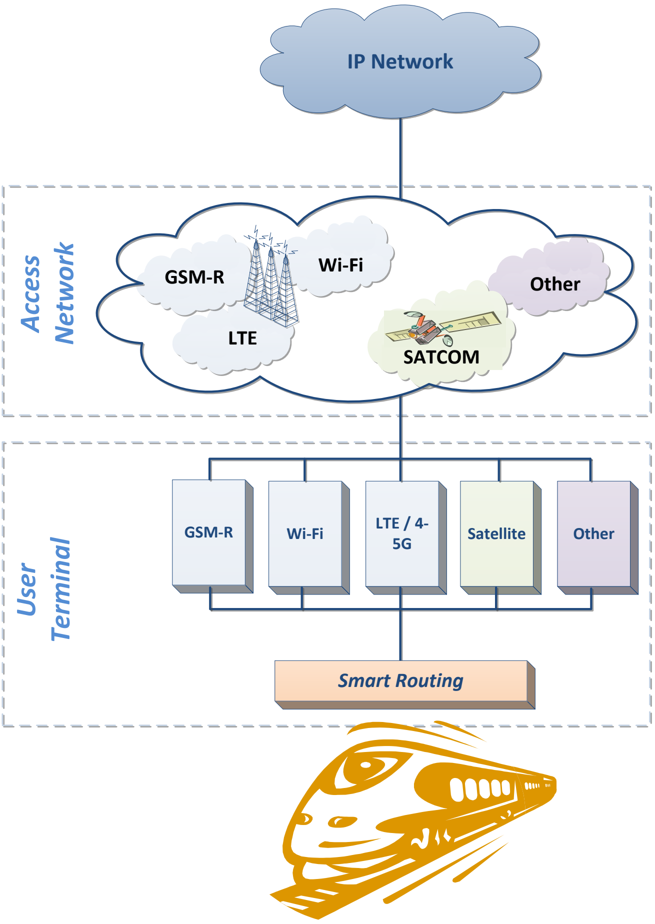


Figure 99: Smart-routing capability to handle vertical handovers

***CRITERION TRACEABILITY***

- FRMCS URS v2.0 (Pr2)

**CRT-MULT-4** FRMCS user terminals shall be able to provide communications taking into account a multi-technology communication architecture. Therefore, terminals (or at least some type of terminals) shall support multi-technology in order to avoid having one different terminal per technology.

***RATIONALE***

Since the FRMCS is going to be made up by different bearers (including legacy GSM-R at least during the first transition period), terminals will be able to implement the use of several bearers. SDR (Software Define Radio) technologies should be supported in order to provide high flexibility to the user terminal whereas reducing costs of the network.

***CRITERION TRACEABILITY***

- FRMCS URS v2.0 (Pr2)

## A.3 NON-TECHNICAL CRITERIA DEFINITION

This section defines the non-functional and non-technical criteria applicable to the SATCOM technologies derived from the FRMCS requirements. Just like with previous sections, each criteria is complemented with a rationale or justification, and with a criterion traceability to the reference documentation (if required). Table 40 of previous sections summarizes the information provided for each criterion.

**CRT-NONT-1** The proposed SATCOM system for the future railway communications architecture shall have a universally assumed sustained lifecycle covering the total timespan of the FRMCS without risk of obsolescence. Due to current estimates of migration from GSM-R, roll-out of the next generation systems is expected around the year 2022. Taking into account reference lifecycles of such systems, a sustainability of minimum 15 years is expected after this date.

***RATIONALE***

GSM-R, the current European railway communications standard, is a derivative of the commercially oriented GSM mobile communications technology standard, and it was intended to build on its commonplace adoption and its versatility for the benefit of rail communications. However, the resulting standard was too far a departure from commercial GSM, and its specialist timeline development resulted in an early obsolescence from a system support perspective, as well as from an operator relevance standpoint. The FRMCS should build on a communications solution which is by all means planned to be sustained from a technical and a market standpoint at least up until FRMCS' planned operational timespan.

***CRITERION TRACEABILITY***

- Survey on operational communications (study for the evolution of the railway communications system), Ref: 37760-496v04 [RD-17]

**CRT-NONT-2** The proposed SATCOM system for the future railway communications architecture shall provide for easy serviceability that has minimal impact on operations, whether it is due to scheduled or unscheduled maintenance/repair. Additionally, the system shall ensure that technical and multitechnology criteria compliance is maintained within the required limits throughout the lifetime of the assemblies. However, during preventative or corrective maintenance, the subsystem may not be able to respect the values quoted in the Basic Parameters; the maintenance rules shall ensure that safety is not prejudiced during these activities.

***RATIONALE***

Satcom systems can be affected by interruptions or failures that do not affect other systems (such as sun-fade interruptions). Additionally, SATCOM for rail systems have been prone to unexpected and recurrent antenna failure by means of external factors, such as inadequate protection. It should be ensured that these factors do not affect the ability of the system to meet the safety performances requirements.

***CRITERION TRACEABILITY***

- Survey on operational communications (study for the evolution of the railway communications system), Ref: 37760-496v04 [RD-17]
- CCS TSI (Technical specifications for interoperability) – EU Decision 2012/88/EU

**CRT-NONT-3** The proposed SATCOM system for the future railway communications architecture shall provide at least an acceptable level of cost efficiency, taking into account full lifecycle costs covering the full lifespan of the selected solution, and as long as technical and functional requirements allow for this option.

***RATIONALE***

Costs are a key decision driver for the selection of a new communication system. The future system shall have at least an “Acceptable” cost efficiency. This is due to the fact that, despite costs not being the key driver for such a system, it should not have a worse costs performance than the existing GSM-R system.

The cost-efficiency of the system has been defined according to several key influencing factors which have an impact on the CapEx and OpEx values.

- Use of Commercial Off the Shelf equipment: The use of commercial equipment allows for a reduction of the costs of both procuring and operating equipment.
- Dedicated infrastructure/Potential for added value services. The potential for sharing infrastructure with other systems and/or providing additional services which could be monetized.
- Duration of deployment: The longer the deployment time the less time infrastructure is made use of and longer that legacy systems have to be kept in place.

| Cost-Efficiency | Description |
|---|---|
| High | A fully COTS based system allows for a reduction in both CapEx and OpEx due to larger volumes, higher industrial competition and resulting lower costs both for infrastructure and systems investments as well as for direct running costs.<br>The use of infrastructure (spectrum, terminals) which is shared with other services and allows for direct revenue from the system. This includes commercial services such as passenger communications.<br>Deployment time of 5 years or less for average Member State. |
| Acceptable | A modified off the shelf system allows for leveraging from existing standards, but due to the COTS solution not fulfilling all necessary requirements, requires certain specific modifications.<br>Some infrastructure can be leveraged to provide additional services outside of the ones required.<br>Deployment time of approximately 10 years for average Member State. |

| | |
|---|---|
| **Low** | A tailor-made solution, especially if entailing a single platform, would typically result in single party development costs with no space for synergies and limited commercial competition, if any at all. This has traditionally resulted in high costs and inevitable monopolistic dominance positions detrimental to cost-efficiency on the side of operators.<br>The system does not provide any leverage which can be used to provide additional services to the required ones.<br>Deployment time of more than 10 years for average Member State.and no potential sources of income. |

Table 52 Proposed cost efficiency levels

A preemptive assessment should consider how specific solutions could benefit from synergies and economies of scale through their widespread use in other applications. Hence, at least an 'acceptable' level of cost efficiency should be targeted, as long as functional and technical requirements allow for such option. While specific cost assessments shall be carried out, it shall be observed that costs are assessed across the full intended lifecycle of the solution, covering all investments to be made, including hardware replacements, overhauls and updates, as well as all direct costs.

***CRITERION TRACEABILITY***

- Survey on operational communications (study for the evolution of the railway communications system), Ref: 37760-496v04 [RD-17]

**CRT-NONT-4** The proposed SATCOM system for the future railway communications architecture shall demonstrate forecasted full lifecycle costs that are, by all acceptable estimates, not higher than those of GSM-R.

***RATIONALE***

Costs are a key decision driver for the selection of a new communication system. Despite costs not being the key driver for such a system, it should not have a worse costs performance than the existing GSM-R system.

At decision level, only preliminary cost benefit estimates may be available. When performed through acceptable best practices and approved by authorized stakeholders and experts, these estimates should clearly point out at a superior cost performance (i.e. lower lifecycle costs) than GSM-R for any candidate system to be regarded as suitable.

***CRITERION TRACEABILITY***

- Survey on operational communications (study for the evolution of the railway communications system), Ref: 37760-496v04 [RD-17]
- Study on migration of railway radio communication system from GSM-R to other solutions, Ref ERA_RS1_DLV_023 [RD-18]

**CRT-NONT-5** The proposed SATCOM system for the future railway communications architecture shall demonstrate a forecasted full lifecycle economic internal rate of return (IRR, alternatively ERR) above the average minimum acceptable rate of return (MARR) set by the target Member States for public investments.

***RATIONALE***

Costs are a key decision driver for the selection of a new communication system. Despite costs not being the key driver for such a system, it should not have a worse costs performance than the existing GSM-R system.

At decision level, only preliminary cost benefit estimates may be available. When performed through acceptable best practices and approved by authorized stakeholders and experts, these estimates should clearly point out at an economic internal rate of return (IRR or more accurately ERR) superior to the minimum acceptable rate of return (MARR) required for public investments in Europe. Although it is not immediate that the required investments will fall upon public entities, and despite there is no universally accepted MARR level across Europe, a conservative average of national standard values can be regarded as a balanced and appropriate benchmark for cost benefit assessments. MARR values for public investments in EU Member States typically range from 3% to 4% for long-time members, and my occasionally climb to 7% for recent members. An up-to-date average should be computed and suitably justified with adequate referencing for actual decision-making.

***CRITERION TRACEABILITY***

- Survey on operational communications (study for the evolution of the railway communications system), Ref: 37760-496v04 [RD-17]
- Study on migration of railway radio communication system from GSM-R to other solutions, Ref ERA_RS1_DLV_023 [RD-18]
- Guide to Cost Benefit Analysis of Investment Projects, DG Regional Policy, July 2014 [RD-19]

**CRT-NONT-6** Standards shall be used to the extent possible to ensure interoperability of the proposed SATCOM system for the future railway communications architecture with communication systems (satellite, terrestrial and possible gap fillers). Additionally, the mandatory standards listed in this table shall be applied in the certification process:

- EN 50126 Railway applications — The specification and demonstration of reliability, availability, maintainability and safety (RAMS)
- EN 50128 Railway applications — Communication, signalling and processing systems — Software for railway control and protection systems
- EN 50129 Railway applications — Communication, signalling and processing systems — Safety related electronic systems for signalling
- EN 50159 Railway applications — Communication, signalling and processing systems — Safety-related communication in transmission systems

***RATIONALE***

The use of open standards ensures interoperability and reduces costs. Additionally, future systems should undergo certification processes to ensure at least mandatory standards are complied with. While specific novel technological solutions may escape the scope of current or short-term standards, the ability to attain certification will continue to be the cornerstone for entry into operational service. For this reason, standardization and applicable regulation for any candidate solution should have at least reached initial draft stage by an active Working Group within a competent organization.

***CRITERION TRACEABILITY***

- Survey on operational communications (study for the evolution of the railway communications system), Ref: 37760-496v04 [RD-17]
- CCS TSI (Technical specifications for interoperability) – EU Decision 2012/88/EU

**CRT-NONT-7** The proposed SATCOM system for the future railway communications architecture shall hold at least a universally accepted technology readiness level (TRL) of 7 or above.

***RATIONALE***

While novel solutions may be assessed while they have still not attained operational status due to insufficient maturity, all candidate technologies should have at least been proven up to full system prototype level in an operational environment. Below this level, it can be safely judged that technologies will be in a level too much undeveloped than required to assure a smooth and well-planned entry into service.

***CRITERION TRACEABILITY***

Survey on operational communications (study for the evolution of the railway communications system), Ref: 37760-496v04

## B. SURVEY QUESTIONS

This annex contains the full set of questions contained in the SOTM & Trains Survey. For each question, the intended respondent is identified (see also Section §7.1.1):

- **[SATCOM]** for satellite communications stakeholders
- **[RAIL]** for railway communications stakeholders
- **[CSP/MNO]** for communications service providers and mobile network operators
- **[ALL]**: these questions should be answered by all participants.

Participants could respond to the Survey by either filling in the questions in this section, or an online form, which was split in two depending on the target audience; see Section §7.1.2 for more details.

### B.1 TRENDS AND NEW DEVELOPMENTS

This section addresses the issues of future trends in the field of satcom technology and services and their potential use in the railway environment. We aim to find out more about the roadmaps of satcom operators, satcom component manufacturers and satellite service providers, taking into account the main requirements from end users of mobile environments.

1. (SATCOM) Which are, in your view, the main trends in SATCOM technologies in the field of SATCOM on-the-move (SOTM)?

   a. Handheld support
   b. Lower spectrum band (S, L and VHF)
   c. Lower satellite constellation orbit (i.e. LEO or MEO)
   d. HTS (Higher spectrum band-Ka and multi-beam scenario)
   e. Improvement in antenna profile and performance
   f. Higher data rates
   g. Waveform with spreading capabilities
   h. Adoption of commercial communication standard, as for example:…
   i. Adoption of customised and property communication protocols
   j. Others (please specify):

| |
|---|
| |

| |
|---|
| The following questions focus on the main obstacles to be overcome in the coming years by the satcom industry in order to penetrate the mobility markets - in particular, those requiring safety communications. |

2. (SATCOM) What are, in your view, the main technology challenges to be faced for satellite technologies providing mobile communication services?

   a. Satellite regulations (i.e. off-axis)
   b. Spectrum efficiency (i.e. cost per bit - OPEX)
   c. Antenna performances
   d. Terminal SWaP (Size, Weight and Power) requirements
   e. Others (please specify):

| |
|---|
| |

3. (SATCOM) What are, in your view, the main non-technological challenges to be faced by the satcom industries regarding satcom use for safety applications/services?

   a. Terminal costs
   b. Return on Investment
   c. Certification
   d. Sustainability
   e. Maturity
   f. Limited market size
   g. Others (please specify):

4. (SATCOM) What do you think are the key drivers that may influence satcom technology adoption in the railway domain?

a. Introduction of the mega-constellations (i.e. Low cost LEO constellations)

b. Network convergence (i.e. 5G) in which satellite communications can be standardised.

c. Technologies enabling bandwidth sharing between terrestrial and satcom bearers

d. Others (please specify):

## B.2 OPERATIONAL ISSUES

This section aims to identify gaps in state-of-the-art satcom technologies and services with regard to providing railway communications, in particular for safety-critical applications (e.g. ETCS data, emergency voice calls, etc). Therefore, the following questions focus on the current capabilities and performances of the deployed systems and technologies available on the market.

5. (SATCOM) Regarding your satcom on the move (SOTM) products and/or services, which frequency bands are they going to be offered for?

a. Ka-band

b. Ku-band

c. X-band

d. C-band

e. L-band

f. Others (please specify):

6. (SATCOM) In what satellite constellation do your solutions offer mobile services?

   a. HEO
   b. GEO
   c. MEO
   d. LEO

7. (SATCOM) Can they support voice call services?

   a. No
   b. Yes, only one-to-one phone calls.
   c. Yes, and also multi-party/conference
   d. Others:

8. (SATCOM) Are your products compliant with railway regulation EN-50155 (e.g. environmental, EMI/EMC, electrical, etc)?

   a. No
   b. Yes
   c. Other response (please specify):

The following questions are also addressed to RAIL stakeholders due to their involvement in relevant European programs, Working Groups, Conferences, etc related to the replacement of GSM-R.

9. (ALL) What are the main constraints or problems that you can envisage for the installation of a new radio technology, in particular a satellite terminal on the train?

a. Conformity with EN-50155 (e.g. environmental, EMI/EMC, electrical, etc.)

b. Train installation verification

c. Interoperability with other railway systems

d. Others (please specify):

10. (ALL) In your view, what are the main problems for satcom use in the railway domain?

a. Lack of coverage throughout the journey (due to tunnels, geography/mountains, buildings, stations, etc)

b. QoS performances, mainly due to the latency when using GEO systems

c. Cost of operation (OPEX)

d. Cost of installation/deployment or terminal on-board (CAPEX)

e. Others (please specify):

### B.3 QOS PERFORMANCES

| |
|---|
| This section aims to investigate the QoS performances provided by solutions available on the market for mobile environments (i.e. SOTM technology), paying special attention to typical railway channel impairments. |

11. (SATCOM) Are your products suitable to operate in a railway environment taking into account that they have to provide countermeasures against the typical impairments for this type of channel

    a. Doppler (e.g. train speed of up to 350 km per hour)
    b. Fast fadings (e.g. periodic micro cuts due to posts)
    c. Slow fadings
    d. Multipath (e.g. due to the catenary reflection when omni antenna is employed)
    e. Off-axis regulation due to the need for low profile antenna
    f. Others (please specify):

| |
|---|
| |

12. (SATCOM) What products and/or services do you offer for this type of environment or similar?

    a. Baseband equipment (modems, routers, etc)
    b. Planar/low profile antennas and/or RF (e.g. ACU, BUC, LNB, etc) devices for remote terminals
    c. Satellite constellation (e.g. LEO, GEO)
    d. Satellite ground stations
    e. Others (please specify):

Can you indicate the name of the technology/product or service that you offer:

| |
|---|
| |

13. (SATCOM) Do you use a standardised air interface?

a. Yes

b. No

|  |
| --- |
|  |

14. (continued) If the previous answer is YES: What communication standard do you employ in your system?

a. DVB-S

b. DVB-S2

c. DVB-S2X

d. DVB-RCS

e. DVB-RCS2

f. DVB-SH

g. ETSI S-MIM

h. IESS (e.g. IESS 308, 309, … ) please specify which one:

i. STANAGs, please specify which one:

j. Other (please specify):

|  |
| --- |
|  |

15. (SATCOM) What specific functionalities are implementing your products in favour of **satcom on the move** scenarios?

a. Signal spreading (configurable)

b. Anti-jamming techniques (Frequency hopping based)

c. Automatic Control Unit for antenna pointing

d. Fast signal acquisition techniques

e. Channel/Block Interleaver

f. Enhanced FEC codes (Turbo codes, LDPC, etc)

g. Fast lost channel detection

h. ACM

i. Automatic Power Control algorithm

j. LL-FEC

k. ARQ

l. Time diversity, Frequency diversity or site diversity

m. Others (please specify):

| |
|---|
| |

16. (SATCOM) What specific services are you offering or going to deploy for mobile scenarios (not necessarily for safety communications)?

| |
|---|
| |

17. (SATCOM) Are you offering or going to deploy services for safety communication networks?

a. Yes

b. No

c. Other response (please specify):

| |
|---|
| |

18. (continued) If the previous answer is YES: What type of service are you going to offer and for what domain?

19. (SATCOM) Can your satcom solutions support the use of handhelds/sat phones?

a. Yes

b. No

c. Other response (please specify):

### B.4 GSM-R EVOLUTION FRAMEWORK

This section aims to obtain information about the views of RAILWAY STAKEHOLDERS on the evolution of the current communication system (GSM-R) towards an all IP-based technology.

20. (RAIL), (CSP/MNO) Are you participating in any working group related to railway communications (e.g. Agency WG's, UIC, ETSI, others?)

a. Yes. Please indicate the name(s): …

b. No.

c. Other response (please specify):

21. (RAIL), (CSP/MNO) Are you aware of the on-going initiatives to investigate the replacement of GSM-R in the mid- term?

a. Yes, S2R

b. Yes, ERA studies

c. Yes, ESA ARTES projects

d. Yes, UIC FRM CS project and others

e. No

f. Other response (please specify):

| |
|---|
| |

22. (RAIL), (CSP/MNO) What are you currently using the GSM-R system for?

a. Railway operational voice services

b. Other voice services (i.e. maintenance)

c. ETCS Level 2 data

d. Other non-critical data, for the operation and maintenance of the railway service (i.e. transmission of logs, information points, sensors, etc). Please indicate an estimation of the bandwidth used.

e. Others (please specify):

| |
|---|
| |

23. (RAIL), (CSP/MNO) Are you currently using other terrestrial communication systems than GSM-R for any of the following? : (i.e. analogue radio, public mobile networks (2G/3G/4G), TETRA, wifi, etc) Please indicate which network/technology for which service; if it is used as backup or as the main link, and an estimation of the bandwidth required.

a. Main railway operational voice services

b. Other voice services (i.e. shunting, maintenance)

c. Train Protection system/signalling (including, for example, communication between interlocking and trackside)

d. Other non-critical data, for the operation and maintenance of the railway service (i.e. transmission of logs, information points, sensors, signalling, etc).

e. Passenger services (information/entertainment/internet on board)

f. Others/ additional information (please specify):

| |
|---|
| |

24. (RAIL), (CSP/MNO) Are you currently using satellite communication systems for any of the following services? Please indicate: which services; if satcom is used as backup or as the main link; and an estimation of the bandwidth required.

a. Main railway operational voice services

b. Other voice services (i.e. shunting, maintenance)

c. Train Protection system/signalling (including, for example, communication between interlocking and trackside)

d. Other non-critical data, for the operation and maintenance of the railway service (i.e. transmission of logs, information points, sensors, signalling, etc).

e. Passenger services (information/entertainment/internet on board)

f. Others/ additional information (please specify):

| |
|---|
| |

25. (RAIL), (CSP/MNO) Is your company thinking about preparing the evolution of the railway communication system by using 4G/LTE? Please give details of what steps have already been taken, if any, towards this evolution (i.e. establishment of a design/discussion group, contacts with other industries/providers, traffic analysis, market research, etc)

a. Yes

b. No, but rather, by using

i. GPRS

ii. TETRA

iii. Wifi

iv. Shared network with other emergency/critical services

v. 5G

vi. SATCOM

c. Others/ additional information:

| |
|---|
| |

26. (RAIL), (CSP/MNO) Do you think that Satcom solutions could have an opportunity to become part of the multi-technology future railway architecture? And what role could Satcom play?

a. Main system just like some other terrestrial systems (e.g. GSM-R, 4G/LTE, …)

b. Only as a complementary and/or backup system to provide coverage to those areas (rural) where terrestrial solutions are difficult to deploy

c. Others (please specify):

| |
|---|
| |

27. (RAIL), (CSP/MNO) In your view, do you think Satcom could be used in any of the following scenarios to provide critical applications? Please provide a justification of your answer.

a. Main stations/shunting yards (many users, low speed...)

b. Dense/urban lines (many users, moderate speed...)

c. Low density/regional lines (fewer users, moderate to high speed...)

d. High speed lines (fewer users, very high speed...)

| |
|---|
| |

28. (RAIL), (CSP/MNO) If you answered YES to any of the points in [24]: in your experience, what are the main hurdles for the adoption of satcom solutions in the railway domain?

a. High CAPEX

b. High OPEX

c. Scarce bandwidth available

d. QoS performances

e. Availability of the service (differences along the route)

f. Others (please specify):

| |
|---|
| |

29. (RAIL), (CSP/MNO) What are your main concerns when considering the adoption of satcom solutions in the railway domain?

a. High CAPEX

b. High OPEX

c. Scarce bandwidth available

d. QoS performances

e. Availability of the service (differences along the route)

f. Others (please specify):

| |
|---|
| |

### B.5 USE OF SATCOM FOR BUSINESS APPLICATIONS

Under the current legal framework, railway infrastructure managers are obliged to offer railway operators a harmonised communication service, which is included in the track access fee, but are not entitled to offer these communication services for other added-value services. This section aims to obtain information regarding the view of ALL STAKEHOLDERS about the possibility of using satcom facilities, should they become available for trackside and railway on board use, for other business applications, without considering the legal constraints that may accompany this option.

30. (ALL) Do you see an opportunity for the provision of business applications through the new railway communication system (e.g. passenger services, goods tracking, etc.)?

a. Yes

b. No

c. Other response (please specify):

| |
|---|
| |

31. (ALL) Do you consider that these business applications are feasible in terms of cost efficiency and return on investment?

a. Yes

b. No

c. Other response (please specify):

| |
|---|
| |

# C. TECHNICAL ASSESSMENT OF SATCOM SOLUTIONS

## C.1 SATCOM SOLUTION 1: IRIDIUM NEXT

| ***Iridium NEXT*** | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-1** | *The "link availability" of the proposed satcom system shall be High.* | NC | According to Iridium documentation, former Iridium system has an availability of 99.9%. For Iridium NEXT there is not information available, but it is expected to keep this availability value. Therefore, and assuming the 99.9% value also for Iridium NEXT, it cannot be considered "High". |
| **CRT-TECH-2** | *The "reliability" of the proposed satcom system shall be High.* | C (Low) | Satellite constellations weakest element regarding reliability are satellites, since they cannot be repaired, only replaced. That's why they tend to be designed for very high reliability. Iridium NEXT, in addition to their 66 satellites, plans 6 in-orbit spare satellites plus 9 ground spare satellites ready to be launched when required. For ground system elements, redundancy is used in order to increase reliability. |
| **CRT-TECH-3** | *The end-to-end error ratio of the proposed satcom system shall be Low.*<br>*Note: Since this criterion only considers the satellite system, the error ratio shall be measured after the last satellite communication* | C | The end-to-end error ratio depends mainly on the FEC used. Current satcom systems have implemented powerful FECs based mainly on turbo codes (e.g. TCC, TPC, LDPC, etc) that enable the use of low Eb/No to assure the minimum required BER and/or PER.<br>Former Iridium, for example, uses a BCH(31,20) FEC code (capable of correcting up to 2 bit errors) for its SBD (Short Burst Data) service. This coded data is also protected by a 16-bit CRC error detection code, which is used jointly with a selective ARQ process. |

| *Iridium NEXT* | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-4a** | *Transfer delay for the proposed satellite system shall be Low.*<br>*Note: It refers to the end-to-end (one-way) delay due to the satellite channel. Therefore, it shall be measured from satellite transmitter to satellite receiver.*<br>*4a: Single-hop required* | **C (High)** | LEO satellites and relative high data rates (up to 512 kbps in uplink) enable the possibility of having low transfer delays for Iridium NEXT (even considering the existence of ISL between satellites in order to route correctly calls/sessions). It is not possible for current Iridium, where the very low data rate increases the transfer delay. |
| **CRT-TECH-4b** | *4b: Double-hop required* | **C (High)** | Due to the low transfer delay expected in a single hop, the double hop is also allowed in terms of transfer delay using Iridium NEXT. On the contrary, former Iridium does not comply with the maximum transfer delay allowed when a double hop is possible due to the limited data rate available. |
| **CRT-TECH-5** | *Delay jitter of the proposed satcom system shall be Low.*<br>*Note: Since this criterion refers to the one-way satellite channel jitter, it shall be measured from satellite transmitter to satellite receiver.* | **C (High)** | Since there exist mechanisms to compensate the delay time variations between packets at IP level, it is assumed that IP-based satcom solutions are capable to comply with a Low delay jitter requirement. And although Iridium voice service is provided by the circuit-switching method, jitter is treated in order to provide a good quality of experience.<br>In addition, since Iridium is a LEO constellation and the lower the orbit the lower the jitter, this criterion is market as a "C (High)". |
| **CRT-TECH-6** | *Network registration delay for the proposed satcom system shall be Normal (with similar values of current GSM-R system).* | C | In the satphone comparison study performed by TelAstra (see [RD-22] for more details), it was observed that Iridium 9555 terminal was able for dialing after turning on the device in 31 to 40 seconds. It is expected that Iridium NEXT will be able to keep these times for future terminals. |
| **CRT-TECH-7** | *The call establishment delay for the proposed satcom system shall be Low.*<br>*Note: as a first reference, GSM-R establishment delays can be considered.* | NC | The call establishment delay for Iridium cannot be considered "Low", since the resources reservation process (circuit-switching method) takes longer than 5 seconds. |

| ***Iridium NEXT*** | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-8** | *The proposed satcom system shall allow (at least) the estimated number of European FRMCS users by 2030 registered simultaneously.* | NC | Former Iridium has the constraint of a maximum of 80 users per cell (of about 318,000 km$^2$). Iridium NEXT will keep this number of (Circuit Switched) users and will add more to their Packet Switched services. This constraint is incompatible with the capacity requirement for railways, since the specific number of users in the area of a cell could be greater than 80. |
| **CRT-TECH-9** | *The proposed satcom system shall provide priority and pre-emption mechanisms.* | C | Former Iridium allows priority and pre-emption, so NEXT is expected to include also this feature for both Circuit Switched and Packet Switched services. |
| **CRT-TECH-10** | *The proposed satcom system shall support Data and Voice services.* | C | Iridium supports both data and voice services. Although Iridium voice applications are mainly processed by its Circuit Switched subsystem, it is also capable to process IP voice services by means of its Packet Switched part. |
| **CRT-TECH-11** | *The proposed satcom system shall support as minimum Low bandwidth applications* | C | Former Iridium is able to provide IP services up to 2.4 kbps. However, ongoing Iridium NEXT will be able to provide IP services up to 512 kbps uplink/1.5 Mbps downlink (in L-band). |
| **CRT-TECH-12** | *The proposed satcom system for the FRMCS shall provide "user-to-user" and "multi-user" types of communications for both voice and data services. In addition, each communication can be bi-directional or uni-directional with any type of asymmetry between forward and return channels (when bi-directional).* | NC | In general, the user to multi-user communication from the remote terminal point of view is not a service offered by SATCOM solutions. Anyhow, all-IP solutions allow the implementation of these services at IP level independently of the bearer.<br>But considering that Iridium (and Iridium NEXT) are "closed" solutions, this service is not provided. |
| **CRT-TECH-13** | *The minimum required coverage of the satcom system shall be Europe.* | C | It is the unique satcom solution providing real worldwide coverage, including polar zones. |
| **CRT-TECH-14** | *The satcom system shall provide communications for remote terminals when stationary and when travelling at speeds up to the maximum allowable line speed or 500 km/h, whichever is the lower.* | C | Solutions that want to provide service for high speed terminals need to implement specific mechanisms to, among others, compensate the Doppler effect. In this case, Iridium has implemented these additional mechanisms since it provides currently service to aircrafts. |

| Iridium NEXT | | | |
|---|---|---|---|
| **Criterion ID** | **Criterion** | **Evaluation** | **Justification** |
| **CRT-TECH-15** | *The proposed satcom system shall be flexible to support (at least) new created apps in the future.* | C (Low) | Despite Iridium and Iridium NEXT are "closed" solutions, new Iridium NEXT will be able to provide some flexibility, mainly to its packet switched for IP services. |
| **CRT-TECH-16** | *The proposed satcom system shall be highly and easily scalable.* | C (Low) | Iridium is a "closed" system that, in addition, operates a low frequency band, which provides less scalability than higher frequency bands. Therefore, this system can be scaled but limited to the architectural design for what was conceived. |
| **CRT-TECH-17** | *The proposed satcom system shall allow the use of the following types of terminals: "On-board (mobile)", "Handheld" and "Fixed".* | C (Low) | It supports several classes of terminals for different environments, involving, on-board, handheld and fix.<br>It is worth to mention that handhelds are (nowadays) only providing service by means of the circuit switched method provided by Iridium. |
| **CRT-TECH-18** | *The proposed satcom system shall provide high level of safety in the information exchanged.* | C (Low) | Iridium provides techniques such as anti-jamming (based on frequency-hopping), fast signal acquisition, block interleavers, enhanced FECs, fast channel loss detection, diverse techniques, etc., which makes this solution safety in front of non-intentional RF interferences. |
| **CRT-TECH-19** | *The proposed satcom system shall provide high level of security in the information exchanged.* | NC | Iridium, just like most of the commercial satcom solutions, do not provide mechanisms to prevent intentional attacks and/or RF interferences. |

Table 53: Iridium NEXT assessment

### C.1.1 Additional information useful for the assessment

#### C.1.1.1 Delay study

Due to Iridium NEXT architecture where user information can travel by different satellites by means of Inter Satellite Links (ISL), delay experienced by a user will depend on each specific case. Considering a *generic* situation in which three satellites are needed to travel from the satellite user to the Gateway (for example), next approximation is done:

$$T_{packet} = T_{tx} + T_{up} + (N-1) \cdot T_{cross} + N \cdot T_{sat} + T_{down}$$

Where,

$T_{tx}$ is the transmission time for a given packet
$T_{up}$ is the propagation delay from ground to the overhead satellite
$T_{cross}$ is the propagation time between satellite cross links
$T_{sat}$ is the processing delay per satellite
This parameter is considered negligible
$T_{down}$ is the propagation time from the satellite to the ground
$N$ is the number of satellite in the node

In order to provide an example, following data is assumed:

Data packet: 120 bytes
Transmission in return link: 512 kbps
Transmission in forward link: 1.5 Mbps
Average number of ISL (Inter-Satellite Links) used: 2 (i.e. 3 satellites)
Satellite processing delay can be considered negligible

Then, the end-to-end transmission packet delay in return link (the most restrictive) passing through an average number of 3 satellites (2 ISL) is:

$T_{tx}$ = packet_size / throughput = 120 bytes / 512 kbps = 1.8 ms

$T_{up} = T_{down}$ = sat_distance / speed = 780 km / 300000 km/sec = 2.6 ms

$T_{cross}$ = crosslink_distance / speed = 4000 km / 300000 km/sec = 13.3 ms

$$\Longrightarrow T_{packet} = 1.8 + 2.6 + 2 \cdot 13.3 + 2.6 = \mathbf{33.6\ ms}$$

At this point, it is worth to highlight the improvement achieved in delay with future NEXT regarding the former Iridium, since the original system was only capable to send data through a channel of 2.4 kbps. It means that only the transmission time ($T_{tx}$) with current system implies a delay of 400 ms:

$$T_{tx-former-Iridium} = 120\ bytes/2.4kbps = 400\ ms$$

Therefore, it can be seen that with future Iridium NEXT transmission delays will take advantage of the LEO constellation with the use of higher data rates than current Iridium.

## C.2 SATCOM SOLUTION 2: MEO / C-BAND

| MEO / C-band | | | |
|---|---|---|---|
| **Criterion ID** | **Criterion** | **Evaluation** | **Justification** |
| **CRT-TECH-1** | *The "link availability" of the proposed satcom system shall be High.* | C | Link budgets performed at Satcom4Rail project [RD-20] estimated a link availability of 99.993%. |
| **CRT-TECH-2** | *The "reliability" of the proposed satcom system shall be High.* | **C (High)** | Space segment reliability of this solution (the weakest element of the satcom solution, since they cannot be repaired, only replaced) is expected to be increased by in-orbit spare satellite(s) and also with ground spare satellite(s).<br>Ground elements reliability is increased by means of redundancy.<br>Railway terminals shall be designed to provide the required MTBF and MTTR figures. |
| **CRT-TECH-3** | *The end-to-end error ratio of the proposed satcom system shall be Low.*<br>*Note: Since this criterion only considers the satellite system, the error ratio shall be measured after the last satellite communication* | C | The end-to-end error ratio depends on those techniques implemented to guarantee service continuity (such as FEC, ARQ, etc). Current satcom systems have implemented powerful FECs based mainly on turbo codes (e.g. TCC, TPC, LDPC, etc.) that enable the use of low Eb/No to assure the minimum required BER and/or PER.<br>Therefore, and considering that the MEO/C-band is a future satcom solution, it is assumed that it will use a communication standard with powerful FEC codes (and other mechanisms) required. |
| **CRT-TECH-4a** | *Transfer delay for the proposed satellite system shall be Low.*<br>*Note: It refers to the end-to-end (one-way) delay due to the satellite channel. Therefore, it shall be measured from satellite transmitter to satellite receiver.*<br>*4a: Single-hop required* | **C (High)** | Transfer delay of this solution will depend on several design parameters of the system, such as altitude of the constellation, bit rate, routing of the information, etc. Within the Satcom4Rail project [RD-20] several scenarios were analysed, and transfer delays between 70 and 125 ms were calculated for a single-hop. |
| **CRT-TECH-4b** | *4b: Double-hop required* | **C (High)** | Assuming values calculated for the single-hop in the Satcom4Rail project [RD-20], a double-hop is also allowed. |

| MEO / C-band | | | |
|---|---|---|---|
| **Criterion ID** | **Criterion** | **Evaluation** | **Justification** |
| **CRT-TECH-5** | *Delay jitter of the proposed satcom system shall be Low.<br>Note: Since this criterion refers to the one-way satellite channel jitter, it shall be measured from satellite transmitter to satellite receiver.* | **C (High)** | There exist mechanisms to compensate the delay time variations between packets at IP level. Therefore, it is assumed that IP-based satcom solutions are capable to comply with a Low delay jitter requirement.<br>In addition, since this solution is based on a MEO constellation and the lower the orbit the lower the jitter, this criterion is market as a "C (High)". |
| **CRT-TECH-6** | *Network registration delay for the proposed satcom system shall be Normal (with similar values of current GSM-R system).* | C | The registration process of the MEO/C-band system can be designed in order to assure a "normal" value similar to current GSM-R performance. |
| **CRT-TECH-7** | *The call establishment delay for the proposed satcom system shall be Low.<br>Note: as a first reference, GSM-R establishment delays can be considered.* | C | The call establishment process of the MEO/C-band system can be designed in order to assure a low delay similar to the one performed by the current GSM-R system (although in the end it will depend on resources and number of users, i.e. the dimensioning of the system). |
| **CRT-TECH-8** | *The proposed satcom system shall allow (at least) the estimated number of European FRMCS users by 2030 registered simultaneously.* | C | Techniques such as frequency reuse shall be used in order to provide service to the estimated number of users by 2030.<br>The higher the number of users, the lower the number of applications to be provided. This way, only critical applications can be assured in a MEO/C-band system. |

| ***MEO / C-band*** | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-9** | *The proposed satcom system shall provide priority and pre-emption mechanisms.* | C | The use in this solution of the DVB-S2X/RCS2 communications standards assures the ability of the system to support and manage priority and pre-emption mechanisms.<br>QoS in DVB standards are basically managed at layer 2, with the use of differentiated queues for different type of traffic (real time, critical data, best effort...).<br>The DAMA mechanism also assures the resources assignment to users by means of several schedule techniques such as Continuous Rate Assignment (CRA), Rate/Volume Based Dynamic Capacity (RBDC/VBDC), Free Capacity Allocation (FCA), etc. |
| **CRT-TECH-10** | *The proposed satcom system shall support Data and Voice services.* | C | This solution is full IP and based on a TDM/MF-TDMA (DAMA) scheme using DVB-S2X / RCS2 standards respectively. Therefore, it will support all kind of IP services (voice and data). It is worth to mention that DVB-RCS2+M includes also a RA carrier for asynchronous data and network signalling. |
| **CRT-TECH-11** | *The proposed satcom system shall support as minimum Low bandwidth applications* | C | Taking into account the correct dimensioning of the system, this MEO/C-band solution is able to provide railway critical narrowband applications. In this case, performance and/or business applications will not be offered by this solution since they require more bandwidth (in fact, high frequency bands, such as Ku and Ka bands will only offer them). |
| **CRT-TECH-12** | *The proposed satcom system for the FRMCS shall provide "user-to-user" and "multi-user" types of communications for both voice and data services. In addition, each communication can be bi-directional or uni-directional with any type of asymmetry between forward and return channels (when bi-directional).* | C | This MEO/C-band system is based on a theoretical future solution. Therefore, and considering that this is an all-IP solution, all these types of communications can be implemented (at least) at IP-level. |

| ***MEO / C-band*** | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-13** | *The minimum required coverage of the satcom system shall be Europe.* | C | This is a theoretical solution defined in the Satcom4Rail project ([RD-20]) that should be designed to provide full coverage to the pan-European area. |
| **CRT-TECH-14** | *The satcom system shall provide communications for remote terminals when stationary and when travelling at speeds up to the maximum allowable line speed or 500 km/h, whichever is the lower.* | C | Communications standards such as DVB-RCS adds specific annexes for mobile environments (referred as DVB-RCS**+M**, in this case), which deal with mobile common effects, such as Doppler. Therefore, this solution will implement specific mechanisms such as Doppler compensation in order to allow speeds up to 500 km/h. |
| **CRT-TECH-15** | *The proposed satcom system shall be flexible to support (at least) new created apps in the future.* | **C (High)** | This is an "open" solution that takes advantage of commercial communications standards (DVB-S2X / RCS2+M), which have been designed to provide high level of flexibility (bandwidth channelization, modcods, etc.). Therefore, this solution can be considered highly flexible. |
| **CRT-TECH-16** | *The proposed satcom system shall be highly and easily scalable.* | C (Low) | The use of the C-band makes this solution scalable but taking into account its spectral bandwidth limitation. |
| **CRT-TECH-17** | *The proposed satcom system shall allow the use of the following types of terminals: "On-board (mobile)", "Handheld" and "Fixed".* | C | Link budgets performed at Satcom4Rail project [RD-20] showed that the use of handhelds were possible even considering a high link availability. |
| **CRT-TECH-18** | *The proposed satcom system shall provide high level of safety in the information exchanged.* | **C (High)** | The MEO/C-band system can be designed in order to allow techniques providing the high level of safety required, such as diversity, enhanced FECs, fast signal acquisition… |
| **CRT-TECH-19** | *The proposed satcom system shall provide high level of security in the information exchanged.* | NC | When this solution was specified within the Satcom4Rail project [RD-20], it was not specified security mechanisms at L1/L2 level, but they could be added if required since this is only a theoretical solution. |

Table 54: MEO / C-band assessment

## C.2.1 Additional information useful for the assessment

### C.2.1.1 Delay study

In order to give some examples about the transmission delay of a MEO/C-band constellation, 2 different examples are provided:

The first one considering a MEO constellation with an altitude of about 5,000 km. Since it is a low altitude, routing is assumed to be done by means of inter-satellite links (ISL). This way, an extra delay has to be considered.

And the second one considering a MEO constellation with an altitude of about 20,000 km. Since it is a high altitude, routing can be done by means of several GES around the world.

Both examples assume following input:

Data packet: 120 bytes
Transmission in return link: 256 kbps
Transmission in forward link: 1 Mbps
Satellite processing delay can be considered negligible

***Example 1: MEO 5,000 km altitude with ISL***

Within this example, it is considered that in average, only 2 satellites (1 ISL) is required to achieve a GES. In addition, distance among satellites of the same orbit is assumed about 10,000 km.

$$T_{packet} = T_{tx} + T_{up} + (N-1) \cdot T_{cross} + N \cdot T_{sat} + T_{down}$$

Where,

$T_{tx}$ is the transmission time for a given packet
$T_{up}$ is the propagation delay from ground to the overhead satellite
$T_{cross}$ is the propagation time between satellite cross links
$T_{sat}$ is the processing delay per satellite
This parameter is considered negligible.
$T_{down}$ is the propagation time from the satellite to the ground
$N$ is the number of satellite in the node

Then, the end-to-end transmission packet delay in return link (the most restrictive) passing through an average number of 2 satellites (1 ISL) is:

$T_{tx}$ = packet_size / throughput = 120 bytes / 256 kbps = 3.7 ms

$T_{up}$ = $T_{down}$ = sat_distance / speed = 5,000 km / 300,000 km/sec = 16.6 ms

$T_{cross}$ = crosslink_distance / speed = 10,000 km / 300,000 km/sec = 33.3 ms

$$\Rightarrow T_{packet} = 3.7 + 16.6 + 1 \cdot 33.3 + 16.6 = \mathbf{70.2\ ms}$$

### *Example 2: MEO 20,000 km altitude without ISL*

In this case no ISL are considered, since the architecture assumes the deployment of as many GES as required in order to satellites always have a GES visible. Therefore:

$$T_{packet} = T_{tx} + T_{up} + T_{down}$$

Where,

$T_{tx}$ is the transmission time for a given packet
$T_{up}$ is the propagation delay from ground to the overhead satellite

$T_{down}$ is the propagation time from the satellite to the ground

Then, the end-to-end transmission packet delay in return link is:

$T_{tx}$ = packet_size / throughput = 120 bytes / 256 kbps = 3.7 ms

$T_{up}$ = $T_{down}$ = sat_distance / speed = 20,000 km / 300,000 km/sec = 66.6 ms

$$\Longrightarrow T_{packet} = 3.7 + 66.6 + 66.6 \cong \mathbf{137\ ms}$$

Results in both examples show that:

MEO solutions reduce transmission delay significantly regarding GEO solutions.

MEO altitude is a key parameter. Lower altitudes reduces delay but increases complexity, for example with the use of ISL (or deploying lots of GES) and requiring more satellites.

## C.3 SATCOM SOLUTION 3: INMARSAT 4 (BGAN) & INMARSAT 6 (ICE)

| ***Inmarsat 4 (BGAN) - Inmarsat 6 (ICE)*** | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-1** | *The "link availability" of the proposed satcom system shall be High.* | NC | According to the study [RD-21] Inmarsat 4 link availability is about 95%. |
| **CRT-TECH-2** | *The "reliability" of the proposed satcom system shall be High.* | C (Low) | For ground system elements, Inmarsat uses redundancy in order to increase reliability. For the satellite constellation, despite satellites are designed with a very high reliability, there are not backup elements. |
| **CRT-TECH-3** | *The end-to-end error ratio of the proposed satcom system shall be Low.*<br>*Note: Since this criterion only considers the satellite system, the error ratio shall be measured after the last satellite communication* | C | The end-to-end error ratio depends mainly on the FEC used (and in general on those techniques implemented to guarantee service continuity).<br>In this sense, Inmarsat 4 provides powerful FEC codes based on turbo codes. Inmarsat 6 is expected to improve even these mechanisms, since its future implementation will take advantage of current/future improvements in this field. |
| **CRT-TECH-4a** | *Transfer delay for the proposed satellite system shall be Low.*<br>*Note: It refers to the end-to-end (one-way) delay due to the satellite channel. Therefore, it shall be measured from satellite transmitter to satellite receiver.*<br>*4a: Single-hop required* | NC | The latency for voice in Circuit-Switching in Inmarsat 4 is around 585 ms. Therefore, the transfer delay in this case cannot be considered "low". |
| **CRT-TECH-4b** | *4b: Double-hop required* | NC | The double-hop transfer delay for the BGAN system cannot be considered "Low", since it exceeds the 0.5 seconds. |

| Inmarsat 4 (BGAN) - Inmarsat 6 (ICE) | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-5** | *Delay jitter of the proposed satcom system shall be Low.*<br>*Note: Since this criterion refers to the one-way satellite channel jitter, it shall be measured from satellite transmitter to satellite receiver.* | C (Low) | Since there exist mechanisms to compensate the delay time variations between packets at IP level, it is assumed that IP-based satcom solutions are capable to comply with a Low delay jitter requirement. And although Inmarsat 4 voice service is provided by the circuit-switching method, jitter is treated in order to provide a good quality of experience.<br>In this case, and considering that the lower the orbit the lower the jitter, this criterion is market as a "C (Low)" since Inmarsat 4/6 are based on GEO constellations. |

| Inmarsat 4 (BGAN) - Inmarsat 6 (ICE) | | | |
|---|---|---|---|
| **Criterion ID** | **Criterion** | **Evaluation** | **Justification** |
| **CRT-TECH-6** | *Network registration delay for the proposed satcom system shall be Normal (with similar values of current GSM-R system).* | NC | Inmarsat 4 (BGAN) terminals requires "2 registration processes" to be able to use Packet Switched services.<br>Each I-4 satellite can generate 19 wide beams and more than 200 narrow spot-beams. These beams can be quickly reconfigured and focused anywhere on Earth to provide extra capacity where needed.<br>The BGAN system requires 2 step connection process. The first step is to Register with the Network, which is opening a *wide beam* connection with one of the I-4 satellites. After registration, the BGAN terminal's phone and SMS messaging services are operational (Circuit Switched). The BGAN may place or receive voice calls or sms messages to anyone in the world.<br>The second step is opening a Data Session (Packet Switched), such as a connection to the Internet. When this happens, the BGAN terminal is connecting to a Narrow Beam of the same I-4 satellite.<br>In addition, within the terminal comparison study performed by TelAstra [RD-22], it is shown that the registration time of the BGAN IsatPhone Pro takes a lot of time (between 72 to 120 seconds) because it needs first to fix its position by means of the GPS system. Despite this first acquisition is expected to be improved, it is only the first step of the registration process (in fact satphones only executes this first step since they only provide service by means of the Circuit Switched system. |

| Inmarsat 4 (BGAN) - Inmarsat 6 (ICE) | | | |
|---|---|---|---|
| **Criterion ID** | **Criterion** | **Evaluation** | **Justification** |
| **CRT-TECH-7** | *The call establishment delay for the proposed satcom system shall be Low.*<br>*Note: as a first reference, GSM-R establishment delays can be considered.* | NC | Inmarsat call establishment delays are:[22]<br>- *Ground-to-air:* 25 s (P95); 30 s (P99).<br>- *Air-to-ground:* 10 s (P95); 15 s (P99)<br>Therefore, this criterion is considered "NC". |
| **CRT-TECH-8** | *The proposed satcom system shall allow (at least) the estimated number of European FRMCS users by 2030 registered simultaneously.* | PC | Inmarsat is able to provide the required service to current GSM-R data users. But it will not be able to provide service also to the estimated numbers of voice services users. |
| **CRT-TECH-9** | *The proposed satcom system shall provide priority and pre-emption mechanisms.* | C | Each I4 connection is established with a certain set of Quality of Service (QoS) parameters, which include the following:<br>- Rate Parameters: Mean Rate and Peak Rate;<br>- Delay Parameters: Target Latency and Discard Latency; and<br>- Connection Type and Priority. |
| **CRT-TECH-10** | *The proposed satcom system shall support Data and Voice services.* | C | I4 supports data and voice services. Although I4 voice applications are mainly processed by its Circuit Switched subsystem, it is also capable to process IP voice services by means of its Packet Switched part. |
| **CRT-TECH-11** | *The proposed satcom system shall support as minimum Low bandwidth applications* | C | Inmarsat 4 provides speeds up to more than 400 kbps. Therefore, it is able to support critical railway applications, and even some performance and/or business applications. |

[22] P95: with a probability of 95%; P99: with a probability of 99%

| Inmarsat 4 (BGAN) - Inmarsat 6 (ICE) | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-12** | *The proposed satcom system for the FRMCS shall provide "user-to-user" and "multi-user" types of communications for both voice and data services. In addition, each communication can be bi-directional or uni-directional with any type of asymmetry between forward and return channels (when bi-directional).* | NC | In general, the user to multi-user communication from the remote terminal point of view is not a service offered by SATCOM solutions. Anyway, solutions based on IP allow the implementation of these services at IP level independently of the bearer. But in this case, considering that Inmarsat 4 is a "closed" solution, this service is not provided (despite most probably it could be offered with some little modifications in the management plane).<br>Communications are always bidirectional, with the asymmetry required. |
| **CRT-TECH-13** | *The minimum required coverage of the satcom system shall be Europe.* | C | Inmarsat 4 is a GEO constellation providing service worldwide (except poles zones). |
| **CRT-TECH-14** | *The satcom system shall provide communications for remote terminals when stationary and when travelling at speeds up to the maximum allowable line speed or 500 km/h, whichever is the lower.* | C | Inmarsat currently provides service to planes. Therefore, it has implemented the mechanisms to allow its use in high-speed mobile environments. |
| **CRT-TECH-15** | *The proposed satcom system shall be flexible to support (at least) new created apps in the future.* | C | Inmarsat (BGAN) offers a high level of configurability that can help this solution to be flexible enough in front of new challenges in the future. |
| **CRT-TECH-16** | *The proposed satcom system shall be highly and easily scalable.* | C (Low) | The use of different techniques (such as frequency reuse) makes this solution scalable but taking into account intrinsic limitations of the L-band. |
| **CRT-TECH-17** | *The proposed satcom system shall allow the use of the following types of terminals: "On-board (mobile)", "Handheld" and "Fixed".* | C (Low) | Inmarsat 4 currently provides all types of terminals, including handhelds. However, handhelds are only available for circuit switched voice and data services. |
| **CRT-TECH-18** | *The proposed satcom system shall provide high level of safety in the information exchanged.* | **C (High)** | Inmarsat provides techniques such as signal spreading, fast signal acquisition, enhanced FECs, fast channel loss detection, diverse techniques, etc., which provide a high level of safety. |
| **CRT-TECH-19** | *The proposed satcom system shall provide high level of security in the information exchanged.* | C | Inmarsat 4 uses authentication and encryption at level 2, providing this way a high level of security. |

Table 55: Inmarsat 4 / Inmarsat 6 assessment

## C.3.1 Additional information useful for the assessment

### C.3.1.1 Delay study

Despite Inmarsat 4 is a narrowband system, it can achieve a throughput of 492 kbps. In this example, we assume a transmission data rate in the return link of 64 kbps, a rate more appropriate to a narrowband system. To calculate the transmission time the following approximation is done:

$$T_{packet} = T_{tx} + T_{up} + T_{down}$$

Where,

$T_{tx}$ is the transmission time for a given packet
$T_{up}$ is the propagation delay from ground to the overhead satellite
$T_{down}$ is the propagation time from the satellite to the ground

In order to provide an example, following data is assumed:

Data packet: 120 bytes
Transmission in return link: 64 kbps

The end-to-end transmission packet delay in return link is:

$T_{tx}$ = packet_size / throughput = 120 bytes / 64000 bps = 15 ms

$T_{up}$ = $T_{down}$ = sat_distance / speed = 36000 km / 300000 km/sec = 120 ms

$$\Longrightarrow T_{packet} = 15 + 120 + 120 = \mathbf{255\ ms}$$

This result shows that the very big part of transmission delay in a GEO narrowband system with a minimum data rate available is due to the GEO satellite.

## C.4 SATCOM SOLUTION 4: GEO / L-BAND BASED ON ANTARES CS (IRIS FOC)

| ***GEO / L-band + ANTARES CS (IRIS FOC)*** | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-1** | *The “link availability” of the proposed satcom system shall be High.* | C (Low) | Unlike the Inmarsat 4 system, it is an "open" solution where a high link availability for safety applications can be considered, since the use of a low frequency band (L-band) helps to this demanding requirement.<br>Anyway, it is also worth to mention that being compliant with the high link availability required may imply the impossibility to provide some types of terminals (basically handhelds). Regarding this issue, it is true that Inmarsat 4 (also a GEO/L-band solution) enables the use of handhelds, but not being compliant with the high link availability criterion. |
| **CRT-TECH-2** | *The “reliability” of the proposed satcom system shall be High.* | **C (High)** | With the aim of increasing reliability and comply with the safety applications requirements, this future (hypothetical) satcom system can be designed with redundancy in both ground and space segments.<br>In addition, railway terminals shall be designed to provide the required MTBF and MTTR figures. |
| **CRT-TECH-3** | *The end-to-end error ratio of the proposed satcom system shall be Low.*<br>*Note: Since this criterion only considers the satellite system, the error ratio shall be measured after the last satellite communication* | C | The end-to-end error ratio depends mainly on the FEC used. Current satcom systems have implemented powerful FECs based mainly on turbo codes (e.g. TCC, TPC, LDPC, etc.) that enable the use of low Eb/No to assure the minimum required BER and/or PER.<br>ANTARES CS also provides powerful FEC codes, such as TCC and LDPC, and also ARQ techniques to improve continuity. |

| GEO / L-band + ANTARES CS (IRIS FOC) | | | |
|---|---|---|---|
| **Criterion ID** | **Criterion** | **Evaluation** | **Justification** |
| **CRT-TECH-4a** | *Transfer delay for the proposed satellite system shall be Low.*<br>*Note: It refers to the end-to-end (one-way) delay due to the satellite channel. Therefore, it shall be measured from satellite transmitter to satellite receiver.*<br>*4a: Single-hop required* | C (Low) | This solution is based on a pure random multiple access scheme providing low data rate in the return link. This low data rate makes the transmission time (Tx) not negligible in front of the delay due to the use of a GEO satellite (of around 250 ms).<br>In addition, the reception process of asynchronous bursts sent requires an iterative processing that is usually greater than the transmission time (it can be estimated as a 1.5 times the Tx [RD-23]).<br>All these issues make the transfer delay in this system near the 500 ms. |
| **CRT-TECH-4b** | *4b: Double-hop required* | NC | Taking into account that a single-hop is close the 500 ms., the double-hop will be close 1 second. |
| **CRT-TECH-5** | *Delay jitter of the proposed satcom system shall be Low.*<br>*Note: Since this criterion refers to the one-way satellite channel jitter, it shall be measured from satellite transmitter to satellite receiver.* | C (Low) | There exist mechanisms to compensate the delay time variations between packets at IP level. Therefore, it is assumed that IP-based satcom solutions are capable to comply with a Low delay jitter requirement.<br>In this case (GEO satcom solution), and considering that the lower the orbit the lower the jitter, this criterion is market as a "C (Low)". |
| **CRT-TECH-6** | *Network registration delay for the proposed satcom system shall be Normal (with similar values of current GSM-R system).* | C | The registration process of the GEO/L-band based on ANTARES CS system can be designed in order to assure a "normal" value. In fact, and taking into account the pure random access method on return link, the network registration could be considered quick. |
| **CRT-TECH-7** | *The call establishment delay for the proposed satcom system shall be Low.*<br>*Note: as a first reference, GSM-R establishment delays can be considered.* | **C (High)** | ANTARES does not require a call establishment since it is based on a pure random access multiple access. It means that voice data packets are sent when they are available without asking for resources. |

| GEO / L-band + ANTARES CS (IRIS FOC) | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-8** | *The proposed satcom system shall allow (at least) the estimated number of European FRMCS users by 2030 registered simultaneously.* | C | This solution uses a highly efficient transmission protocol suitable for thousands of connected objects simultaneously. In addition, this system also benefits from the frequency reuse mechanism. |
| **CRT-TECH-9** | *The proposed satcom system shall provide priority and pre-emption mechanisms.* | C | ANTARES defines several CoS in order to prioritize traffic. Moreover, additional implementation at IP level (L3) can be added by means of QoS IP routers. |
| **CRT-TECH-10** | *The proposed satcom system shall support Data and Voice services.* | C (Low) | Despite the ANTARES CS is oriented to data bursts messages, it supports both voice and data services. However, the number of calls shall be limited in order not to degrade the performance of the system and to reduce efficiency. |
| **CRT-TECH-11** | *The proposed satcom system shall support as minimum Low bandwidth applications* | C (Low) | ANTARES CS has been conceived to support low bandwidth applications. Therefore, it could support critical railway applications. |
| **CRT-TECH-12** | *The proposed satcom system for the FRMCS shall provide "user-to-user" and "multi-user" types of communications for both voice and data services. In addition, each communication can be bi-directional or uni-directional with any type of asymmetry between forward and return channels (when bi-directional).* | C | Since this is an "open" all-IP solution, every type of communications can be implemented at least at IP level.<br>The ANTARES standard provides all types of communications except the user-to-multiuser from the remote terminal point of view (i.e. on the return link). In this case, an implementation at IP level in the control plane should be required. |
| **CRT-TECH-13** | *The minimum required coverage of the satcom system shall be Europe.* | C | This theoretical solution shall be designed in order to cover (at least) the European region. |
| **CRT-TECH-14** | *The satcom system shall provide communications for remote terminals when stationary and when travelling at speeds up to the maximum allowable line speed or 500 km/h, whichever is the lower.* | C | ANTARES CS has been conceived as an standard for Air Traffic Management (ATM). Therefore it includes all the mechanisms to support high speed. |
| **CRT-TECH-15** | *The proposed satcom system shall be flexible to support (at least) new created apps in the future.* | C (Low) | ANTARES CS has been designed taking into account flexibility. This way, different carriers type with different spreading factors are available. |

| ***GEO / L-band + ANTARES CS (IRIS FOC)*** | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-16** | *The proposed satcom system shall be highly and easily scalable.* | C (Low) | ANTARES CS can make use of different techniques (such as channelisation of 200 kHz or frequency reuse) to offer scalability (but considering intrinsic limitations of the L-band). |
| **CRT-TECH-17** | *The proposed satcom system shall allow the use of the following types of terminals: "On-board (mobile)", "Handheld" and "Fixed".* | PC | Handhelds were not taken into account in the ANTARES communication standard definition. Therefore, handhelds are not supported. |
| **CRT-TECH-18** | *The proposed satcom system shall provide high level of safety in the information exchanged.* | **C (High)** | This standard was designed in order to meet the stringent safety requirements for the ATM applications. |
| **CRT-TECH-19** | *The proposed satcom system shall provide high level of security in the information exchanged.* | NC | This standard is not implementing specific functionality to tackle the intentional interferences effect on the L1 and L2. |

Table 56: GEO / L-band based on ANTARES CS (IRIS FOC) assessment

### C.4.1 Additional information useful for the assessment

#### C.4.1.1 Delay study

Since this solution is based in a GEO satellite, the main part of the transmission delay will be the propagation delay between terminal and satellite and vice-versa. Therefore, the following approximation is done:

$$T_{packet} = T_{tx} + T_{rx} + T_{up} + T_{down}$$

Where,

$T_{tx}$ is the transmission time for a given packet
$T_{rx}$ is the reception time for a given packet

$T_{up}$ is the propagation delay from ground to the overhead satellite
$T_{down}$ is the propagation time from the satellite to the ground

It is worth mentioning that previous formula includes the "$T_{rx}$" because the processing of the reception of an asynchronous CDMA burst based on E-SSA cannot be considered a negligible value. In fact, it can be assumed (refer to [RD-23]) that the reception process can take in mean a period of time of 1.5 times de transmission time (i.e. $T_{rx} = 1.5*T_{tx}$).

In order to provide an example, following data is assumed:

Data packet: 120 bytes
Transmission in return link: 10 kbps

Since the delay study is performed with the most restrictive channel, it will be made with the return channel.

Then, the end-to-end transmission packet delay in return link is:

$T_{tx}$ = packet_size / throughput = 120 bytes / 10000 bps = 96 ms

$T_{rx} = 1.5*T_{tx} = 144$ ms

$T_{up} = T_{down}$ = sat_distance / speed = 36000 km / 300000 km/sec = 120 ms

$$\Rightarrow T_{packet} = 96 + 144 + 120 + 120 = \mathbf{480\ ms}$$

This result shows that in this case, the low throughput provided by the ANTARES CS and the non-negligible processing time at the reception, **duplicates** the transmission delay regarding those solutions providing higher throughput. On the contrary, the random access provided by ANTARES has the advantage of sending the information when it is available without the need of requesting for resources.

## C.5 SATCOM SOLUTION 5: THURAYA

| Thuraya | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-1** | *The "link availability" of the proposed satcom system shall be High.* | NC | Thuraya is a "closed" satcom system mainly oriented to voice communications via CS (Circuit-Switching). It is also a GEO/L-band (like Inmarsat 4 and ANTARES previously analysed). It enables the use of handhelds but not providing the high link availability required for safety applications (since this system was not designed for this type of services). |
| **CRT-TECH-2** | *The "reliability" of the proposed satcom system shall be High.* | C (Low) | Thuraya, which terminals are fully compatible with GSM networks, offers GSM as a backup system, increasing this way the reliability. It is worth to mention that Thuraya has an agreement with more than 300 GSM partners worldwide in order to offer GSM roaming services when satellite is not available. |
| **CRT-TECH-3** | *The end-to-end error ratio of the proposed satcom system shall be Low.*<br>*Note: Since this criterion only considers the satellite system, the error ratio shall be measured after the last satellite communication* | C | The end-to-end error ratio depends mainly on the FEC used.<br>Thuraya relies on the GMR-1 standard, which provides lots of FEC codes, such as convolutional, turbo codes, Reed Solomon, etc. |
| **CRT-TECH-4a** | *Transfer delay for the proposed satellite system shall be Low.*<br>*Note: It refers to the end-to-end (one-way) delay due to the satellite channel. Therefore, it shall be measured from satellite transmitter to satellite receiver.*<br>*4a: Single-hop required* | C (Low) | The low data rate provided by Thuraya in the return link, along with the GEO satellite, increases the transfer delay up to around 300 ms (see delay study below). |
| **CRT-TECH-4b** | *4b: Double-hop required* | NC | Taking into account the delay estimated for the single-hop, the transfer delay for a double-hop scenario exceeds the 500 ms. |

| Thuraya | | | |
|---|---|---|---|
| **Criterion ID** | **Criterion** | **Evaluation** | **Justification** |
| **CRT-TECH-5** | *Delay jitter of the proposed satcom system shall be Low.*<br>*Note: Since this criterion refers to the one-way satellite channel jitter, it shall be measured from satellite transmitter to satellite receiver.* | C (Low) | This solution is similar to Inmarsat 4. In the same way, and assuming that there exist mechanisms to compensate the delay time variations between packets at IP level, IP-based satcom solutions are capable to comply with a Low delay jitter requirement. And although Thuraya voice service is provided by the circuit-switching method, jitter is treated in order to provide a good quality of experience. In this case, and considering that the lower the orbit the lower the jitter, this criterion is market as a "C (Low)" since Thuraya is based on a GEO constellation. |
| **CRT-TECH-6** | *Network registration delay for the proposed satcom system shall be Normal (with similar values of current GSM-R system).* | C | In the terminal comparison study performed by TelAstra [RD-22], it is shown that the registration time of the Thuraya XT handheld terminal takes a short time to register, since GPS functions are performed in background. |
| **CRT-TECH-7** | *The call establishment delay for the proposed satcom system shall be Low.*<br>*Note: as a first reference, GSM-R establishment delays can be considered.* | NC | Thuraya is based on the same standard than BGAN (GMR-1 - Geo Mobile Radio). Therefore, it is expected to have similar call establishment delays. |
| **CRT-TECH-8** | *The proposed satcom system shall allow (at least) the estimated number of European FRMCS users by 2030 registered simultaneously.* | NC | Thuraya's satellites have been designed to achieve network capacity of about 13,750 telephone channels, which is insufficient to provide service to current number of GSM-R users. |
| **CRT-TECH-9** | *The proposed satcom system shall provide priority and pre-emption mechanisms.* | C | Thuraya offers the possibility to add several QoS policies in order to apply different priorities to the generated traffic. |
| **CRT-TECH-10** | *The proposed satcom system shall support Data and Voice services.* | C | Thuraya is a satellite system compatible with GSM that has been created to provide mainly voice services. In addition, it is also able to provide data services in a circuit-switched mode (9.6 kbps), but also in a packet-switched mode just like the GPRS system (up to 60 kbps downlink/15 kbps uplink). |

| Thuraya | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-11** | *The proposed satcom system shall support as minimum Low bandwidth applications* | C (Low) | Thuraya offers narrowband solutions, which are enough for critical railway applications. |
| **CRT-TECH-12** | *The proposed satcom system for the FRMCS shall provide "user-to-user" and "multi-user" types of communications for both voice and data services. In addition, each communication can be bi-directional or uni-directional with any type of asymmetry between forward and return channels (when bi-directional).* | NC | Just like previous "closed" satcom solution, Thuraya is not able to provide the user to multi-user communication from the remote terminal point of view, since this is not a service offered usually by satcom solutions. |
| **CRT-TECH-13** | *The minimum required coverage of the satcom system shall be Europe.* | C | Thuraya provides currently satellite coverage to the whole pan-European area with 2 GEO satellites. |
| **CRT-TECH-14** | *The satcom system shall provide communications for remote terminals when stationary and when travelling at speeds up to the maximum allowable line speed or 500 km/h, whichever is the lower.* | NC | Thuraya relies on GMR-1 (GEO Mobile Radio 1) communication standard, which does not include special mechanisms to support high speeds up to 500 km/h, but only to less than 200 km/h. |
| **CRT-TECH-15** | *The proposed satcom system shall be flexible to support (at least) new created apps in the future.* | C (Low) | Despite Thuraya is a "closed" solution, it can offer some flexibility according to user needs. |
| **CRT-TECH-16** | *The proposed satcom system shall be highly and easily scalable.* | NC | Thuraya cannot offer scalability since it is not able to provide service to the whole number of current GSM-R users. |
| **CRT-TECH-17** | *The proposed satcom system shall allow the use of the following types of terminals: "On-board (mobile)", "Handheld" and "Fixed".* | C (Low) | Thuraya currently provides all types of terminals, including handhelds. However, handhelds are only available for circuit switched voice and data services. |
| **CRT-TECH-18** | *The proposed satcom system shall provide high level of safety in the information exchanged.* | C (Low) | Some techniques, such as diversity, are used by Thuraya to provide a level of safety. |

| Thuraya | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-19** | *The proposed satcom system shall provide high level of security in the information exchanged.* | NC | Thuraya, just like most of the commercial satcom solutions, do not provide mechanisms to prevent intentional attacks and/or RF interferences. |

Table 57: Thuraya assessment

### C.5.1 Additional information useful for the assessment

#### C.5.1.1 Delay study

Since this system is based on a GEO satellite operating with an L-band, the theoretical delay expected is very similar to the one calculated with the Inmarsat 4 system. Therefore, see section §C.3.1.1 for more details.

Thuraya can provide data communications up to 60 kbps downlink and 15 kbps uplink. Therefore, in this example we assume a transmission data rate in the return link of 15 kbps. To calculate the transmission time the following approximation is done:

$$T_{packet} = T_{tx} + T_{up} + T_{down}$$

Where,

$T_{tx}$ is the transmission time for a given packet
$T_{up}$ is the propagation delay from ground to the overhead satellite
$T_{down}$ is the propagation time from the satellite to the ground

In order to provide an example, following data is assumed:

Data packet: 120 bytes

Transmission in return link: 15 kbps

The end-to-end transmission packet delay in return link is:

$T_{tx}$ = packet_size / throughput = 120 bytes / 15000 bps = 64 ms

$T_{up}$ = $T_{down}$ = sat_distance / speed = 36000 km / 300000 km/sec = 120 ms

$$\Longrightarrow T_{packet} = 64 + 120 + 120 = \mathbf{304\ ms}$$

This result shows that, although the big part of transmission delay in the Thuraya system is due to the GEO satellite, the very low data rate causes a non-negligible delay of more than 60 ms.

## C.6 SATCOM SOLUTION 6: GEO / S-BAND BASED ON S-MIM

| ***GEO / S-band*** | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-1** | *The "link availability" of the proposed satcom system shall be High.* | C (Low) | Link budgets performed at Satcom4Rail project [RD-20] estimated a link availability of 99.993%, and demonstrated that this very high link availability was feasible with a GEO/S-band solution.<br>On the contrary, this very high link availability could difficult the use of some type of terminals, such as handhelds of even simple on-board terminals (i.e. it could imply the use of directive antennas). |
| **CRT-TECH-2** | *The "reliability" of the proposed satcom system shall be High.* | C (Low) | Satellites are in general designed with a very high reliability, since they cannot be repaired.<br>For ground segment elements, mechanisms such as redundancy and backup can be used in order to increase reliability. |
| **CRT-TECH-3** | *The end-to-end error ratio of the proposed satcom system shall be Low.*<br>*Note: Since this criterion only considers the satellite system, the error ratio shall be measured after the last satellite communication* | C | The S-MIM standard has been conceived to be used in a mobile environment. Therefore, it implements several mechanisms to assure continuity and the minimum required PER, such as FEC (turbo codes), channel interleaving and scrambling.<br>An Automatic Repeat Request (ARQ - stop-and-wait) mechanism combined with a terminal rate control at gateway side has also been defined, in order to provide retransmission (ARQ) and be able to tune the maximum rate at which terminals transmit in order to cope with congestion. |

| ***GEO / S-band*** | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-4a** | *Transfer delay for the proposed satellite system shall be Low.*<br>*Note: It refers to the end-to-end (one-way) delay due to the satellite channel. Therefore, it shall be measured from satellite transmitter to satellite receiver.*<br>*4a: Single-hop required* | NC | Since this solution is based on S-MIM communication standard, in the return link the E-SSA random multiple access providing a low data rate is used (about 5 kbps). This low data rate makes the transmission time (Tx) not negligible in front of the delay due to the use of a GEO satellite (of around 250 ms).<br>In addition, the reception process of asynchronous bursts sent requires an iterative processing that can be even greater than the transmission time.<br>All these issues make the transfer delay in this system around the 500 ms.<br>It is also worth to mention that in the forward link (where the DVB-SH protocol is used), channel impairments are counteracted by means of coding combined with a long time interleaver at the physical or link layer level, increasing this way the delay on forward link, as well. |
| **CRT-TECH-4b** | *4b: Double-hop required* | NC | Since double hop transactions represents the double transmission delay that a single-hop transaction, it does not comply either. |
| **CRT-TECH-5** | *Delay jitter of the proposed satcom system shall be Low.*<br>*Note: Since this criterion refers to the one-way satellite channel jitter, it shall be measured from satellite transmitter to satellite receiver.* | C (Low) | There exist mechanisms to compensate the delay time variations between packets at IP level. Therefore, it is assumed that IP-based satcom solutions are capable to comply with a Low delay jitter requirement.<br>In this case (GEO satcom solution), and considering that the lower the orbit the lower the jitter, this criterion is market as a "C (Low)". |
| **CRT-TECH-6** | *Network registration delay for the proposed satcom system shall be Normal (with similar values of current GSM-R system).* | C | The registration process of the GEO/S-band system can be designed in order to assure a "normal" value. In fact, and taking into account the pure random access method on return link, the network registration could be considered short. |

| GEO / S-band | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-7** | *The call establishment delay for the proposed satcom system shall be Low.*<br>*Note: as a first reference, GSM-R establishment delays can be considered.* | **C (High)** | The GEO/S-band system with S-MIM communication standard does not require a call establishment process since it is based on a pure random access scheme. It means that voice data packets are sent when they are available without asking for resources. |
| **CRT-TECH-8** | *The proposed satcom system shall allow (at least) the estimated number of European FRMCS users by 2030 registered simultaneously.* | C | The combination of the use of a very high efficient transmission protocol and other mechanisms such as frequency reuse, makes this solution suitable for thousands of users. |
| **CRT-TECH-9** | *The proposed satcom system shall provide priority and pre-emption mechanisms.* | C | The S-MIM communication standard provides different Service Segments, which can provide differentiated services and QoS. In addition, external elements at IP level (such as QoS IP routers) can be added to provide extra prioritization mechanisms. |
| **CRT-TECH-10** | *The proposed satcom system shall support Data and Voice services.* | PC | This GEO/S-band solution is based on the S-MIM communication standard, which relies on DVB-SH on forward link and on E-SSA on return link, a pure random access scheme. Despite it is a packet switched solution based on IP, it supports mainly data services, since voice applications makes the system more inefficient when the number of simultaneous voice applications increase (due to the random access). |
| **CRT-TECH-11** | *The proposed satcom system shall support as minimum Low bandwidth applications* | C (Low) | The S-MIM communication standard supports low bandwidth applications (up to 5 kbps). |
| **CRT-TECH-12** | *The proposed satcom system for the FRMCS shall provide "user-to-user" and "multi-user" types of communications for both voice and data services. In addition, each communication can be bi-directional or uni-directional with any type of asymmetry between forward and return channels (when bi-directional).* | C | Since this is an "open" all-IP solution, every type of communications can be implemented at least at IP level.<br>The S-MIM standard provides all types of communications except the user-to-multiuser from the remote terminal point of view. In this case, an implementation at IP level in the control plane should be required. |

| GEO / S-band | | | |
|---|---|---|---|
| **Criterion ID** | **Criterion** | **Evaluation** | **Justification** |
| **CRT-TECH-13** | *The minimum required coverage of the satcom system shall be Europe.* | C | This is a generic solution based on GEO/S-band satellite constellation. Therefore, it shall be designed in order to cover (at least) the European region.<br>Currently, the Eutelsat 10A is the satellite providing S-band coverage to Europe, although not all the pan-European area is covered. Therefore, new satellites should be deployed for this future solution. |
| **CRT-TECH-14** | *The satcom system shall provide communications for remote terminals when stationary and when travelling at speeds up to the maximum allowable line speed or 500 km/h, whichever is the lower.* | C | The S-MIM communication standard was designed to support mobile terminals, and it includes mechanisms to support high speeds. |
| **CRT-TECH-15** | *The proposed satcom system shall be flexible to support (at least) new created apps in the future.* | C (Low) | The S-MIM standard offers some flexibility, since for example the forward link defines 2 different schemes (based on OFDM and TDM), and the return link provides 3 sets of service segments and 2 different air interfaces (asynchronous SSA and synchronous QS-CDMA). |
| **CRT-TECH-16** | *The proposed satcom system shall be highly and easily scalable.* | C (Low) | S-MIM can make use of different techniques (such as frequency reuse) to offer scalability (but considering intrinsic limitations of the S-band). |
| **CRT-TECH-17** | *The proposed satcom system shall allow the use of the following types of terminals: "On-board (mobile)", "Handheld" and "Fixed".* | C | GEO/S-band systems are able to support handhelds, such as the S-MIM system.<br>It is worth mentioning that the use of handhelds could imply a link availability not as high as required for safety critical requirements. |
| **CRT-TECH-18** | *The proposed satcom system shall provide high level of safety in the information exchanged.* | **C (High)** | The S-MIM standard provides many mechanisms to counteract interferences, since it was designed to live together with terrestrial systems. For example, the forward link provides very deep interleavers and the return link a high spreading factor. |

| GEO / S-band | | | |
|---|---|---|---|
| **Criterion ID** | **Criterion** | **Evaluation** | **Justification** |
| **CRT-TECH-19** | *The proposed satcom system shall provide high level of security in the information exchanged.* | PC | The S-MIM standard does not provide specifics mechanisms to prevent intentional attacks and/or RF interferences, but the spreading in the return link is beneficial for security. |

Table 58: GEO / S-band (S-MIM CS) assessment

## C.6.1 Additional information useful for the assessment

### C.6.1.1 Delay study

Since this solution is based in a GEO satellite, the main part of the transmission delay will be the propagation delay between terminal and satellite and vice-versa. Therefore, the following approximation is done:

$$T_{packet} = T_{tx} + T_{rx} + T_{up} + T_{down}$$

Where,

$T_{tx}$ is the transmission time for a given packet
$T_{rx}$ is the reception time for a given packet
$T_{up}$ is the propagation delay from ground to the overhead satellite
$T_{down}$ is the propagation time from the satellite to the ground

Observe that within this case the formula includes also a ”$T_{rx}$” (just like the previous solution including the ANTARES CS). It is due to the fact that the time spent processing the reception of an asynchronous CDMA burst based on E-SSA cannot be considered a negligible value. An approximation is done at this point assuming a similar value that ANTARES, where the reception process can take in mean a period of time of 1.5 times de transmission time (i.e. $T_{rx} = 1.5*T_{tx}$).

In order to provide an example, following data is assumed:

Data packet: 120 bytes
Transmission in return link: 5 kbps

Since the delay study is performed with the most restrictive channel, it will be made with the return channel.

Then, the end-to-end transmission packet delay in return link is:

$T_{tx}$ = packet_size / throughput = 120 bytes / 5000 bps = 192 ms

$T_{rx}$ = 1.5*$T_{tx}$ = 288 ms

$T_{up}$ = $T_{down}$ = sat_distance / speed = 36000 km / 300000 km/sec = 120 ms

$$\Longrightarrow T_{packet} = 192 + 288 + 120 + 120 = \mathbf{720\ ms}$$

This result shows that the low data rate along with the iterative processing at reception side causes a very high transmission delay.

### C.7 SATCOM SOLUTION 7: GEO / C-BAND BASED ON DVB-S2X / DVB-RCS2

| GEO / C-band | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-1** | *The "link availability" of the proposed satcom system shall be High.* | C (Low) | Link availabilities in GEO C-band systems (taking into account satellite parameter from current deployments) can be reached when adequate terminal performances are selected (e.g. BUC power, antenna size/type and modem configuration) and considering the maximum data rate (i.e. low date rate) of the railway applications assumed in the scope of this assessment. |
| **CRT-TECH-2** | *The "reliability" of the proposed satcom system shall be High.* | **C (High)** | Satellites are in general designed with a very high reliability, since they cannot be repaired. In addition, and considering that lots of satcom solutions currently deployed are based on GEO/C-band systems, redundancy can be assumed for a possible GEO solution operating the C-band.<br>For ground segment elements, mechanisms such as redundancy and backup can be used in order to increase reliability.<br>Finally, MTBF and MTTR requirements shall be considered when designing railway terminals in order to comply with reliability criterion. |
| **CRT-TECH-3** | *The end-to-end error ratio of the proposed satcom system shall be Low.*<br>*Note: Since this criterion only considers the satellite system, the error ratio shall be measured after the last satellite communication* | C | DVB-S2X/RCS2 standards provides mechanisms to guarantee high level of service continuity implementing mechanisms such as FEC, LL-FEC, retransmissions (ARQ), etc. Therefore, this GEO/C-band solution based on these standards is able to provide a low end-to-end error ratio. |

| GEO / C-band | | | |
|---|---|---|---|
| **Criterion ID** | **Criterion** | **Evaluation** | **Justification** |
| **CRT-TECH-4a** | *Transfer delay for the proposed satellite system shall be Low.*<br>*Note: It refers to the end-to-end (one-way) delay due to the satellite channel. Therefore, it shall be measured from satellite transmitter to satellite receiver.*<br>*4a: Single-hop required* | C (Low) | A GEO satcom solution minimum transfer delay is limited by the distance between terminal and satellite, which is around 250 ms.<br>The C-band with DVB-S2/DVB-RCS2+M communication standards can assure a minimum data rate to a satcom system capable to make the data transmission (quasi) negligible in front of the 250 ms due to the GEO satellite. |
| **CRT-TECH-4b** | *4b: Double-hop required* | NC | The double hop transfer delay for a GEO solution is not compliant with railway requirements with independence of the frequency band used, since only considering the propagation delay to a GEO satellite is around 500 ms. |
| **CRT-TECH-5** | *Delay jitter of the proposed satcom system shall be Low.*<br>*Note: Since this criterion refers to the one-way satellite channel jitter, it shall be measured from satellite transmitter to satellite receiver.* | C (Low) | Just like previous "opened" GEO satcom solutions, this criterion is marked as a "C (Low)", since there exist mechanisms to compensate the delay time variations between packets at IP level, but the lower the orbit the lower the delay jitter. |
| **CRT-TECH-6** | *Network registration delay for the proposed satcom system shall be Normal (with similar values of current GSM-R system).* | C | Assuming a good network dimensioning according to the estimated throughput, the registration process of the GEO/C-band system based on DVB-S2 / DVB-RCS2 communication standards can take a "normal" time similar to current GSM-R performance. |
| **CRT-TECH-7** | *The call establishment delay for the proposed satcom system shall be Low.*<br>*Note: as a first reference, GSM-R establishment delays can be considered.* | C | The call establishment process of the GEO/C-band system based on IP and DAMA access scheme can be designed in order to assure a low delay similar to the one performed by the current GSM-R system. It requires the correct dimensioning of the network resources according to throughput requirements. |

| GEO / C-band | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-8** | *The proposed satcom system shall allow (at least) the estimated number of European FRMCS users by 2030 registered simultaneously.* | C | Techniques such as frequency reuse shall be used in order to provide service to the estimated number of users by 2030.<br>It is worth to mention that C-band is narrowband. Therefore, and since the number of applications supported by a system are related to the frequency band capacity and the number of users, this satcom solution will only provide critical applications to railway users. |
| **CRT-TECH-9** | *The proposed satcom system shall provide priority and pre-emption mechanisms.* | C | The design of this solution will include priority and pre-emption mechanisms. In fact, the use of the DVB-S2X/RCS2 communications standards assures the ability of the system to support and manage QoS, which in DVB standards is basically managed at layer 2, with the use of differentiated queues for different types of traffic (real time, critical data, best effort...).<br>The DAMA mechanism also assures the resources assignment to users by means of several schedule techniques such as Continuous Rate Assignment (CRA), Rate/Volume Based Dynamic Capacity (RBDC/VBDC), Free Capacity Allocation (FCA), etc. |
| **CRT-TECH-10** | *The proposed satcom system shall support Data and Voice services.* | C | This solution is full IP and based on a DAMA scheme using DVB-S2X / RCS2 standards. Therefore, it will support all kind of IP services (voice and data). |
| **CRT-TECH-11** | *The proposed satcom system shall support as minimum Low bandwidth applications* | C | Taking into account a correct dimensioning of the system, a GEO/C-band is able to provide railway critical narrowband applications. In this case, performance and/or business applications will not be offered by this solution since they require more bandwidth (in fact, high frequency bands, such as Ku and Ka bands will only offer them). |

| GEO / C-band | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-12** | *The proposed satcom system for the FRMCS shall provide "user-to-user" and "multi-user" types of communications for both voice and data services. In addition, each communication can be bi-directional or uni-directional with any type of asymmetry between forward and return channels (when bi-directional).* | C | This solution is based on DVB-S2X and DVB-RCS2+M standards, which allow most of the communications types required except the multicast on the return link (i.e. the user to multi-user from the remote terminal point of view). In this case, an extra implementation at IP level should be required to support this particular communication type. |
| **CRT-TECH-13** | *The minimum required coverage of the satcom system shall be Europe.* | C | This is a generic solution based on GEO/C-band satellite constellation. Therefore, satellites should be selected in order to provide full coverage to the pan-European area.<br>Currently, solutions like the Intelsat EpicNG provide C-band coverage (and Ku-band in this case) to the pan-European area. |
| **CRT-TECH-14** | *The satcom system shall provide communications for remote terminals when stationary and when travelling at speeds up to the maximum allowable line speed or 500 km/h, whichever is the lower.* | C | The air interface has a relevant impact on the error budget along with the frequency band (C-band). GEO satellite contribution is neglected due to use of very good reference clocks and no movement of the satellite. Therefore, DVB-S2X and RCS2**+M** standards are going to support speeds up to 500 Km/h without problems (since they provide the mechanisms for high-speed environments, such as Doppler compensation). |
| **CRT-TECH-15** | *The proposed satcom system shall be flexible to support (at least) new created apps in the future.* | **C (High)** | Since this solution is based on DVB-S2X/RCS2+M standards (which have been designed to provide high level of flexibility with lots of modcods and bandwidth channelization), this system can be considered highly flexible, enabling higher modcods that increase the efficiency of the system. |
| **CRT-TECH-16** | *The proposed satcom system shall be highly and easily scalable.* | **C (High)** | Despite C-band spectrum limitations, this solution can offer high scalability by means of techniques such as multi-beam and frequency reuse. |

| GEO / C-band | | | |
|---|---|---|---|
| **Criterion ID** | **Criterion** | **Evaluation** | **Justification** |
| **CRT-TECH-17** | *The proposed satcom system shall allow the use of the following types of terminals: "On-board (mobile)", "Handheld" and "Fixed".* | PC | The combination of "GEO" + "C-band" satcom solutions does not support handhelds. In fact, there is not a commercial GEO/C satellite solution providing currently a service with handhelds. |
| **CRT-TECH-18** | *The proposed satcom system shall provide high level of safety in the information exchanged.* | **C (High)** | GEO/C-band systems taking advantage of DVB-S2X/RCS2+M standards can provide techniques for safety purposes, such as diversity, enhanced FECs, fast signal acquisition… |
| **CRT-TECH-19** | *The proposed satcom system shall provide high level of security in the information exchanged.* | NC | Commercial standards such as DVB-D2X/RCS2+M are not implementing specific functionalities to counteract intentional interferences effects on the L1 and L2. |

Table 59: GEO / C-band (DVB-S2X and DVB-RCS2 CS) assessment

## C.7.1 Additional information useful for the assessment

### C.7.1.1 Delay study

Since this system is based on a GEO satellite operating with an low frequency band (C-band), the theoretical delay expected is very similar to the one calculated with the Inmarsat 4 system. Therefore, see section §C.3.1.1 for more details.

## C.8 SATCOM SOLUTION 8: GEO / X-BAND

| GEO / X-band | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-1** | *The "link availability" of the proposed satcom system shall be High.* | NC | High link availability required for safety critical applications is very difficult to obtain in GEO / X-band satcom solutions, taking into account that this frequency band is higher than S and C bands. In this case, elements required to achieve the high link availability will suppose impossible elements to deploy, such as BUC power or antenna size. |
| **CRT-TECH-2** | *The "reliability" of the proposed satcom system shall be High.* | **C (High)** | For future "opened" solutions in X-band, it can be assumed that both space and ground segments can be designed with redundancy in order to achieve the required reliability. |
| **CRT-TECH-3** | *The end-to-end error ratio of the proposed satcom system shall be Low.*<br>*Note: Since this criterion only considers the satellite system, the error ratio shall be measured after the last satellite communication* | C | This GEO/X-band solution relies on DVB-S2X/RCS2 standards, which provides mechanisms to guarantee high level of service continuity defining, among others, FEC codes and ARQ mechanisms. Therefore, this solution is able to provide a low end-to-end error ratio. |
| **CRT-TECH-4a** | *Transfer delay for the proposed satellite system shall be Low.*<br>*Note: It refers to the end-to-end (one-way) delay due to the satellite channel. Therefore, it shall be measured from satellite transmitter to satellite receiver.*<br>*4a: Single-hop required* | C (Low) | A GEO satcom solution minimum transfer delay is limited by the distance between terminal and satellite, which is around 250 ms.<br>The X-band assuming DVB-S2/DVB-RCS2+M communication standards can assure a minimum data rate to a satcom system capable to make the data transmission (quasi) negligible in front of the 250 ms due to the GEO satellite. |
| **CRT-TECH-4b** | *4b: Double-hop required* | NC | The double hop transfer delay for a GEO solution is not compliant with railway requirements with independence of the frequency band used, since only considering the propagation delay to a GEO satellite is around 500 ms. |

| GEO / X-band | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-5** | *Delay jitter of the proposed satcom system shall be Low.<br>Note: Since this criterion refers to the one-way satellite channel jitter, it shall be measured from satellite transmitter to satellite receiver.* | C (Low) | Just like previous "opened" GEO satcom solutions, this criterion is marked as a "C (Low)", since there exist mechanisms to compensate the delay time variations between packets at IP level, but the lower the orbit the lower the delay jitter. |
| **CRT-TECH-6** | *Network registration delay for the proposed satcom system shall be Normal (with similar values of current GSM-R system).* | C | Assuming a good network dimensioning according to the estimated throughput, the registration process of the GEO/X-band system based on DVB-S2 / DVB-RCS2 communication standards can take a "normal" time similar to current GSM-R performance. |
| **CRT-TECH-7** | *The call establishment delay for the proposed satcom system shall be Low.<br>Note: as a first reference, GSM-R establishment delays can be considered.* | C | The call establishment process of the GEO/X-band system based on IP and DAMA access scheme can be designed in order to assure a low delay similar to the one performed by the current GSM-R system. It requires the correct dimensioning of the network resources according to throughput requirements. |
| **CRT-TECH-8** | *The proposed satcom system shall allow (at least) the estimated number of European FRMCS users by 2030 registered simultaneously.* | C | Techniques such as frequency reuse shall be used in order to provide service to the estimated number of users by 2030.<br>With X-band railway safety critical applications could be offered. |
| **CRT-TECH-9** | *The proposed satcom system shall provide priority and pre-emption mechanisms.* | C | The design of this solution shall include priority and pre-emption mechanisms. It can be assured by the use of the DVB-S2X/RCS2 communications standards, since they support and manage layer 2 QoS with the use of differentiated queues for different types of traffic (real time, critical data, best effort...).<br>The DAMA mechanism also assures the resources assignment to users by means of several schedule techniques such as Continuous Rate Assignment (CRA), Rate/Volume Based Dynamic Capacity (RBDC/VBDC), Free Capacity Allocation (FCA), etc. |

| GEO / X-band | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-10** | *The proposed satcom system shall support Data and Voice services.* | C | This solution is full IP and based on a DAMA scheme using DVB-S2X / RCS2 standards. Therefore, it will support all kind of IP services (voice and data). |
| **CRT-TECH-11** | *The proposed satcom system shall support as minimum Low bandwidth applications* | C | With the correct dimensioning of the system, a GEO/X-band satcom solution is able to provide railway critical narrowband applications. |
| **CRT-TECH-12** | *The proposed satcom system for the FRMCS shall provide "user-to-user" and "multi-user" types of communications for both voice and data services. In addition, each communication can be bi-directional or uni-directional with any type of asymmetry between forward and return channels (when bi-directional).* | C | Just like the previous GEO/C-band solution, this GEO/X-band solution is based on DVB-S2X and DVB-RCS2+M standards, which allow most of the communications types required except the multicast on the return link (i.e. the user to multi-user from the remote terminal point of view). Therefore, an extra implementation at IP level should be required to support this particular communication type. |
| **CRT-TECH-13** | *The minimum required coverage of the satcom system shall be Europe.* | C | Just like previous solutions in S and C bands, this is a generic solution (based on GEO/X-band satellite constellation in this case), which satellites should be selected in order to provide full coverage to the pan-European area.<br>For example, GovSat-1 satellite, which launch date is expected for the third quarter 2017, will provide coverage (among others) in X-band and also in Ka-band (military reserved) to the pan-European area. |
| **CRT-TECH-14** | *The satcom system shall provide communications for remote terminals when stationary and when travelling at speeds up to the maximum allowable line speed or 500 km/h, whichever is the lower.* | C | As it has been explained previously, the selection of the air interface has a relevant impact on the error budget along with the frequency band (X-band). The GEO satellite contribution to this error is negligible due to the use of very good reference clocks and no movement of the satellite. Therefore, the use of communications standards considering mobility effects and their compensations (such as DVB-S2X and RCS2**+M**, for example), will enable high-speed environments up to 500 km/h (or more). |

| GEO / X-band | | | |
|---|---|---|---|
| **Criterion ID** | **Criterion** | **Evaluation** | **Justification** |
| **CRT-TECH-15** | *The proposed satcom system shall be flexible to support (at least) new created apps in the future.* | **C (High)** | DVB-S2X/RCS2+M standards have been designed to provide high level of flexibility with lots of modcods and bandwidth channelization. Therefore, this GEO/X-band system based on these standards can be considered highly flexible, enabling higher modcods that increase the efficiency of the system. |
| **CRT-TECH-16** | *The proposed satcom system shall be highly and easily scalable.* | C | This solution can offer high scalability by means of techniques such as multi-beam and frequency reuse. |
| **CRT-TECH-17** | *The proposed satcom system shall allow the use of the following types of terminals: "On-board (mobile)", "Handheld" and "Fixed".* | PC | Handhelds are not available for GEO satellites on X-band. |
| **CRT-TECH-18** | *The proposed satcom system shall provide high level of safety in the information exchanged.* | **C (High)** | DVB-S2X/RCS2+M standards can provide techniques for safety purposes, such as diversity, enhanced FECs, fast signal acquisition… Therefore, this GEO/X-band solution can make use of these mechanisms to provide the level of safety required. |
| **CRT-TECH-19** | *The proposed satcom system shall provide high level of security in the information exchanged.* | NC | Commercial standards such as DVB-D2X/RCS2+M are not implementing specific functionalities to counteract intentional interferences effects on the L1 and L2. |

Table 60: GEO / X-band (DVB-S2X and DVB-RCS2 CS) assessment

### C.8.1 Additional information useful for the assessment

#### C.8.1.1 Delay study

Since this system is based on a GEO satellite operating with an low frequency band (X-band), the theoretical delay expected is very similar to the one calculated with the Inmarsat 4 system. Therefore, see section §C.3.1.1 for more details.

### C.9 SATCOM SOLUTION 9: SMARTLNB

| *SmartLNB* | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-1** | *The "link availability" of the proposed satcom system shall be High.* | NC | Since SmartLNB system has not been conceived to provide critical services, the link availability provided is not meeting this demanding link availability requirement. |
| **CRT-TECH-2** | *The "reliability" of the proposed satcom system shall be High.* | **C (High)** | Despite the SmartLNB terminals are low cost, the satcom solution is based on a GEO/Ku-band system. If finally this solution is feasible to provide safety applications for railways, redundancy at both space and ground segments can (and shall) be provided, assuring this way the high reliability required. In addition, more robust and reliable terminals will be required for on-board, in order to comply with MTBF and MTTR figures than commercial ones. |
| **CRT-TECH-3** | *The end-to-end error ratio of the proposed satcom system shall be Low.*<br>*Note: Since this criterion only considers the satellite system, the error ratio shall be measured after the last satellite communication* | C | On the forward link, this solution relies on the DVB-S2 standard, which defines mechanisms to assure a high level of continuity. On return link, although the transmission is asynchronous with a random access scheme, a special receiver with a Successive Interference Cancellation (SIC) mechanism is able to decode messages if the traffic load is under control. Traffic load is managed by means of congestion control mechanisms. |
| **CRT-TECH-4a** | *Transfer delay for the proposed satellite system shall be Low.*<br>*Note: It refers to the end-to-end (one-way) delay due to the satellite channel. Therefore, it shall be measured from satellite transmitter to satellite receiver.*<br>*4a: Single-hop required* | NC | On return-link, despite the pure random access mechanism requires a non-negligible time on reception due to an iterative process, the data rate of 160 kbps makes the transfer delay is around 255 ms. |

| ***SmartLNB*** | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-4b** | *4b: Double-hop required* | NC | The double hop transfer delay for a GEO solution is not compliant with railway requirements with independence of the frequency band used, since only considering the propagation delay to a GEO satellite is around 500 ms. |
| **CRT-TECH-5** | *Delay jitter of the proposed satcom system shall be Low.*<br>*Note: Since this criterion refers to the one-way satellite channel jitter, it shall be measured from satellite transmitter to satellite receiver.* | C (Low) | Just like previous "opened" GEO satcom solutions, this criterion is marked as a "C (Low)", since there exist mechanisms to compensate the delay time variations between packets at IP level, but the lower the orbit the lower the delay jitter. |
| **CRT-TECH-6** | *Network registration delay for the proposed satcom system shall be Normal (with similar values of current GSM-R system).* | C | The registration process of the SmartLNB system (GEO/Ku-band) can be designed in order to assure a "normal" value. In fact, and taking into account the pure random access method on return link, the network registration could be considered short. |
| **CRT-TECH-7** | *The call establishment delay for the proposed satcom system shall be Low.*<br>*Note: as a first reference, GSM-R establishment delays can be considered.* | **C (High)** | The SmartLNB system does not require resources request to send data messages (it is based on a pure random access (RA) scheme). It means that is does not spend time establishing a data session. |
| **CRT-TECH-8** | *The proposed satcom system shall allow (at least) the estimated number of European FRMCS users by 2030 registered simultaneously.* | C | This solution uses a highly efficient transmission protocol suitable for thousands of connected terminals. In addition, the use of broadband frequency bands (Ku, Ka) and other techniques such as frequency reuse enable the use of this system for the estimated number of railway users by 2030. |
| **CRT-TECH-9** | *The proposed satcom system shall provide priority and pre-emption mechanisms.* | C | The F-SIM communication standard provides a QoS based on several "service class" definitions, being capable this way to prioritize traffic. |

| *SmartLNB* | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-10** | *The proposed satcom system shall support Data and Voice services.* | PC | SmartLNB is a packet switched solution that supports mainly data services based on bursts messages. Voice services can be supported but limited on number, since this solution is based on the F-SIM, a pure random access standard conceived for data applications. This way, the higher the number of simultaneous voice calls, the lower the efficiency of the system. |
| **CRT-TECH-11** | *The proposed satcom system shall support as minimum Low bandwidth applications* | C | SmartLNB supports low bandwidth applications (up to 160 kbps). |
| **CRT-TECH-12** | *The proposed satcom system for the FRMCS shall provide "user-to-user" and "multi-user" types of communications for both voice and data services. In addition, each communication can be bi-directional or uni-directional with any type of asymmetry between forward and return channels (when bi-directional).* | C | The weak point of this solution regarding the types of communications is the multicast on the return link (just like most of the satcom solutions, since it is not a service usually offered by satcom). Therefore, it should be implemented at IP level. |
| **CRT-TECH-13** | *The minimum required coverage of the satcom system shall be Europe.* | C | SmartLNB takes advantage of Ku and Ka bands satellites. Therefore, satellites providing coverage to the full pan-European area can (and shall) be selected. Currently, this technology is used by Eutelsat, which has lots of satellites providing coverage to Europe, such as the 3ºEast. |
| **CRT-TECH-14** | *The satcom system shall provide communications for remote terminals when stationary and when travelling at speeds up to the maximum allowable line speed or 500 km/h, whichever is the lower.* | PC | This solution takes advantage of the F-SIM communication standard, which currently is able to assure mobility up to 130 km/h without Doppler pre-compensation. This pre-compensation could be implemented for higher speeds support. |

| ***SmartLNB*** | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-15** | *The proposed satcom system shall be flexible to support (at least) new created apps in the future.* | C (Low) | The F-SIM standard offers flexibility in both forward and return links. Forward link is based on DVB-S2 standard, which provides high flexibility (as it has been commented previously), and on return link the F-SIM relies on an E-SSA random access scheme, which provides flexibility adding several types of channelization bandwidth (from 2.5 to 10 MHz), spreading factors (from 16 to 256), frame payload sizes, etc. |
| **CRT-TECH-16** | *The proposed satcom system shall be highly and easily scalable.* | **C (High)** | The use of the Ku-band provides this solution with a high level of scalability, being able also to take advantage of techniques such as multi-beam and frequency reuse.<br>In addition, the F-SIM standard offers the possibility of using this solution in several frequency bands, such as C, Ku and Ka bands, adding even more scalability to this solution. |
| **CRT-TECH-17** | *The proposed satcom system shall allow the use of the following types of terminals: "On-board (mobile)", "Handheld" and "Fixed".* | PC | High frequency bands such as Ku do not make possible the use of handhelds. In addition, fixed and on-board terminals shall use directive antennas, making them more complex (and expensive) than low frequency band terminals. |
| **CRT-TECH-18** | *The proposed satcom system shall provide high level of safety in the information exchanged.* | **C (High)** | The F-SIM standard provides mechanisms to counteract interferences, since in forward link it relies on the DVB-S2 standard, and on return link, the E-SSA RA scheme implemented provides, for example, high spreading factors. |
| **CRT-TECH-19** | *The proposed satcom system shall provide high level of security in the information exchanged.* | PC | The F-SIM standard, just like the S-MIM, does not provide specific mechanisms to prevent intentional attacks and/or RF interferences, but the spreading in the return link is beneficial for security. |

Table 61: SmartLNB assessment

### C.9.1 Additional information useful for the assessment

#### C.9.1.1 Delay study

Since this solution is based in a GEO satellite, the main part of the transmission delay will be the propagation delay between terminal and satellite and vice-versa. Therefore, the following approximation is done:

$$T_{packet} = T_{tx} + T_{rx} + T_{up} + T_{down}$$

Where,

$T_{tx}$ is the transmission time for a given packet
$T_{rx}$ is the reception time for a given packet
$T_{up}$ is the propagation delay from ground to the overhead satellite
$T_{down}$ is the propagation time from the satellite to the ground

Observe that within this case the formula includes also a "$T_{rx}$" (just like the previous solution including the ANTARES CS). It is due to the fact that the time spent processing the reception of an asynchronous CDMA burst based on E-SSA cannot be considered a negligible value. An approximation is done at this point assuming a similar value that ANTARES, where the reception process can take in mean a period of time of 1.5 times de transmission time (i.e. $T_{rx} = 1.5*T_{tx}$).

In order to provide an example, following data is assumed:

Data packet: 120 bytes
Transmission in return link: 160 kbps

Since the delay study is performed with the most restrictive channel, it will be made with the return channel.

Then, the end-to-end transmission packet delay in return link is:

$T_{tx}$ = packet_size / throughput = 120 bytes / 160000 bps = 6 ms

$T_{rx}$ = 1.5*$T_{tx}$ = 9 ms

$T_{up}$ = $T_{down}$ = sat_distance / speed = 36000 km / 300000 km/sec = 120 ms

$$\Longrightarrow T_{packet} = 6 + 9 + 120 + 120 = \mathbf{255\ ms}$$

This result shows that in this case, the higher throughput provided by the F-SIM CS than the other pure random multiple access standards based on E-SSA (like ANTARES or S-MIM) makes the transmission delay smaller.

## C.10 SATCOM SOLUTION 10: GEO / KU-BAND BASED ON DVB-S2X / DVB-RCS2

| ***GEO / Ku-band*** | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-1** | *The "link availability" of the proposed satcom system shall be High.* | NC | Since Ku-band is a very high frequency band, it is more affected by weather conditions than low frequency bands. This issue implies that systems operating at high frequency bands have higher signal attenuation (or less system margin). For Ku-band, attenuation is about 0.5 - 2 dB.<br>Elements required (BUC power, antenna size...) to achieve the very high link availability required operating at Ku-band would require impossible values in order to close the link budget. |
| **CRT-TECH-2** | *The "reliability" of the proposed satcom system shall be High.* | **C (High)** | Since lots of GEO/Ku-band satcom solutions are currently available and are also expected to be available in the future, backup and/or redundancy can be assumed for the space segment of this solution. In the same way, ground segment can be duplicated in order to provide redundancy, increasing this way the reliability of the solution.<br>On-board terminals shall be designed to provide the required MTBF and MTTR figures. |
| **CRT-TECH-3** | *The end-to-end error ratio of the proposed satcom system shall be Low.*<br>*Note: Since this criterion only considers the satellite system, the error ratio shall be measured after the last satellite communication* | C | DVB-S2X/RCS2 standards provides mechanisms to guarantee high level of service continuity. For example, they define mechanisms such as FEC, LL-FEC and ARQ (among others) for this purpose. Therefore, this GEO/Ku-band solution is able to provide a low end-to-end error ratio. |

| GEO / Ku-band | | | |
|---|---|---|---|
| **Criterion ID** | **Criterion** | **Evaluation** | **Justification** |
| **CRT-TECH-4a** | *Transfer delay for the proposed satellite system shall be Low.*<br>*Note: It refers to the end-to-end (one-way) delay due to the satellite channel. Therefore, it shall be measured from satellite transmitter to satellite receiver.*<br>*4a: Single-hop required* | C (Low) | A GEO satcom solution minimum transfer delay is limited by the distance between terminal and satellite, which is around 250 ms.<br>Since a GEO / Ku-band satcom system based on DVB-S2/DVB-RCS2+M communication standards is broadband, delay related with the data transmission is negligible in front of the 250 ms due to the GEO satellite. |
| **CRT-TECH-4b** | *4b: Double-hop required* | NC | The double hop transfer delay for a GEO solution is not compliant with railway requirements with independence of the frequency band used, since only considering the propagation delay to a GEO satellite is around 500 ms. |
| **CRT-TECH-5** | *Delay jitter of the proposed satcom system shall be Low.*<br>*Note: Since this criterion refers to the one-way satellite channel jitter, it shall be measured from satellite transmitter to satellite receiver.* | C (Low) | Just like previous "opened" GEO satcom solutions, this criterion is marked as a "C (Low)", since there exist mechanisms to compensate the delay time variations between packets at IP level, but the lower the orbit the lower the delay jitter. |
| **CRT-TECH-6** | *Network registration delay for the proposed satcom system shall be Normal (with similar values of current GSM-R system).* | C | Assuming a good network dimensioning according to the estimated throughput, the registration process of the GEO/Ku-band system based on DVB-S2 / DVB-RCS2 communication standards can take a "normal" time similar to current GSM-R performance. |
| **CRT-TECH-7** | *The call establishment delay for the proposed satcom system shall be Low.*<br>*Note: as a first reference, GSM-R establishment delays can be considered.* | C | In the same way that previous "opened" satcom systems, the call establishment process of the GEO/Ku-band system based on IP and DAMA access scheme can be designed in order to assure a low delay similar to the one performed by the current GSM-R system. It requires the correct dimensioning of the network resources according to throughput requirements. |

| GEO / Ku-band | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-8** | *The proposed satcom system shall allow (at least) the estimated number of European FRMCS users by 2030 registered simultaneously.* | C | The use of a TDM/MF-TDMA (DAMA) mechanisms based on DVB-S2X/RCS2 respectively will help, along with the use of some other techniques such as frequency reuse, to allow the estimated users by 2030. In addition, the use of the Ku-band can enable not only critical applications, but also performance and/or business applications. |
| **CRT-TECH-9** | *The proposed satcom system shall provide priority and pre-emption mechanisms.* | C | The design of this solution shall include priority and pre-emption mechanisms. It can be assured by the use of the DVB-S2X/RCS2 communications standards, since they support and manage layer 2 QoS with the use of differentiated queues for different types of traffic (real time, critical data, best effort...).<br>The DAMA mechanism also assures the resources assignment to users by means of several schedule techniques such as Continuous Rate Assignment (CRA), Rate/Volume Based Dynamic Capacity (RBDC/VBDC), Free Capacity Allocation (FCA), etc. |
| **CRT-TECH-10** | *The proposed satcom system shall support Data and Voice services.* | C | Generic GEO/Ku-band IP satcom solutions are able to provide voice and data IP services. |
| **CRT-TECH-11** | *The proposed satcom system shall support as minimum Low bandwidth applications* | **C (High)** | Generic satcom GEO / Ku-band solution can support not only low bandwidth applications, but also broadband applications. It means that critical railway applications can be supported and also some other such as performance and/or business apps.<br>It is worth mentioning that Ku and mainly Ka bands can take advantage of High Throughput Satellites (HTS) to offer users very high data rates. |

| GEO / Ku-band | | | |
|---|---|---|---|
| **Criterion ID** | **Criterion** | **Evaluation** | **Justification** |
| **CRT-TECH-12** | *The proposed satcom system for the FRMCS shall provide "user-to-user" and "multi-user" types of communications for both voice and data services. In addition, each communication can be bi-directional or uni-directional with any type of asymmetry between forward and return channels (when bi-directional).* | C | Just like previous "open" solutions, the weak point of the GEO/Ku-band solution regarding the types of communications is the multicast on the return link, since it is not a service usually offered by satcom. Therefore, it should be implemented at IP level. |
| **CRT-TECH-13** | *The minimum required coverage of the satcom system shall be Europe.* | C | Currently, lots of satellites provide Ku-band coverage to Europe. Some examples previously commented are the Intelsat EpicNG (also providing service in C-band) or the Eutelsat 3ºEast. |
| **CRT-TECH-14** | *The satcom system shall provide communications for remote terminals when stationary and when travelling at speeds up to the maximum allowable line speed or 500 km/h, whichever is the lower.* | C | As it has been explained previously, the selection of the air interface has a relevant impact on the error budget along with the frequency band (Ku-band). The GEO satellite contribution to this error is negligible due to the use of very good reference clocks and no movement of the satellite. Therefore, the use of communications standards considering mobility effects and their compensations (such as DVB-S2X and RCS2**+M**, for example) enable high-speed environments up to 500 km/h (or more). |
| **CRT-TECH-15** | *The proposed satcom system shall be flexible to support (at least) new created apps in the future.* | **C (High)** | Since this solution is based on DVB-S2X/RCS2+M standards (which have been designed to provide high level of flexibility with lots of modcods and bandwidth channelization schemes), this system can be considered highly flexible, enabling higher modcods that increase the efficiency of the system. |
| **CRT-TECH-16** | *The proposed satcom system shall be highly and easily scalable.* | **C (High)** | The use of the Ku-band provides this solution with a high level of scalability, being able also to take advantage of techniques such as multi-beam and frequency reuse. |

| GEO / Ku-band | | | |
|---|---|---|---|
| **Criterion ID** | **Criterion** | **Evaluation** | **Justification** |
| **CRT-TECH-17** | *The proposed satcom system shall allow the use of the following types of terminals: "On-board (mobile)", "Handheld" and "Fixed".* | PC | High frequency bands such as Ku do not make possible the use of handhelds. In addition, fixed and on-board terminals shall use directive antennas, making them more complex (and expensive) than low frequency band terminals. |
| **CRT-TECH-18** | *The proposed satcom system shall provide high level of safety in the information exchanged.* | **C (High)** | DVB-S2X/RCS2+M standards can provide techniques for safety purposes, such as diversity, enhanced FECs, fast signal acquisition… Therefore, this GEO/Ku-band solution can make use of these mechanisms to provide the level of safety required. |
| **CRT-TECH-19** | *The proposed satcom system shall provide high level of security in the information exchanged.* | NC | Commercial standards such as DVB-D2X/RCS2+M are not implementing specific functionalities to counteract intentional interferences effects on the L1 and L2. |

Table 62: GEO / Ku-band (DVB-S2X and DVB-RCS2) assessment

### C.10.1 Additional information useful for the assessment

#### C.10.1.1 Delay study

Taking into account the high data rates achievable by a GEO / Ku-band satcom system, the main part of the transmission delay will be the propagation delay between terminal and satellite and vice-versa. Therefore, the following approximation is done:

$$T_{packet} = T_{tx} + T_{up} + T_{down}$$

Where,

$T_{tx}$ is the transmission time for a given packet
$T_{up}$ is the propagation delay from ground to the overhead satellite

$T_{down}$ is the propagation time from the satellite to the ground

In order to provide an example, following data is assumed:

Data packet: 120 bytes
Transmission in return link: 500 kbps
Transmission in forward link: 2 Mbps

Then, the end-to-end transmission packet delay in return link is:

$T_{tx}$ = packet_size / throughput = 120 bytes / 500000 bps = 1.92 ms

$T_{up}$ = $T_{down}$ = sat_distance / speed = 36000 km / 300000 km/sec = 120 ms

$$\Longrightarrow T_{packet} = 1.92 + 120 + 120 \cong \mathbf{242\ ms}$$

This result shows that the very big part of transmission delay in a GEO / Ku-band (and also Ka-band) system is due to the GEO satellite. The data rate could be even greater than the considered one, but transmission delay will not be smaller than the ~240 ms, i.e. the time due to the GEO satellite.

## C.11 SATCOM SOLUTION 11: INMARSAT 5 (GLOBAL XPRESS)

| ***Inmarsat 5 (Global Xpress)*** | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-1** | *The "link availability" of the proposed satcom system shall be High.* | NC | Ka-band is a very high frequency band. Therefore, it is more affected by weather conditions than low frequency bands. This issue implies that systems operating at high frequency bands have higher signal attenuation (or less system margin). For Ka-band, attenuation is about 5 - 10 dB.<br>Despite the use of HTS with small beams concentrating more power to a small area helps to the use of this frequency band, the gain caused by the use of HTS is oriented to increase the date rate, and not to have more margin for rain fade.<br>Anyway, elements required (BUC power, antenna size...) to achieve the very high link availability required operating at Ka-band would require not reasonable values to close the link budget.<br>For the Global Xpress system, maximum link availability expected (%) for a 60cm dish is 99.9 % (and most probably taking into account a very low data rate) is shown at figure below. |
| **CRT-TECH-2** | *The "reliability" of the proposed satcom system shall be High.* | **C (High)** | The number of GEO/Ka-band satcom solutions is expected to increase in the following years. Therefore, it will be possible to design a solution with satellite redundancy.<br>Most systems providing service currently have redundancy or backup ground segment elements (just like Global Xpress), providing this way a high reliability.<br>Finally, railway terminals shall also be designed to provide the required MTBF and MTTR figures. |

| Inmarsat 5 (Global Xpress) | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-3** | *The end-to-end error ratio of the proposed satcom system shall be Low.*<br>*Note: Since this criterion only considers the satellite system, the error ratio shall be measured after the last satellite communication* | C | Just like previous GEO/Ku-band solution based on DVB standards family, Global Xpress (Inmarsat 5) implements, among others mechanisms, ACM (Adaptive Coding Modulation), which dynamically is able to change the coding (FEC) and the modulation of a terminal according to their specific transmission conditions (for example if it is affected by bad weather conditions).<br>Mechanisms like ACM and ARQ makes Global Xpress capable to assure continuity having a low end-to-end error ratio. |
| **CRT-TECH-4a** | *Transfer delay for the proposed satellite system shall be Low.*<br>*Note: It refers to the end-to-end (one-way) delay due to the satellite channel. Therefore, it shall be measured from satellite transmitter to satellite receiver.*<br>*4a: Single-hop required* | C (Low) | Inmarsat 5 is a GEO / Ka-band constellation. It means that the minimum transfer delay is limited by the distance between terminal and satellite, which is about 250 ms.<br>Data rates provided by Inmarsat 5 are very high, so delay related with the data transmission is negligible in front of the 250 ms due to the GEO satellite. |
| **CRT-TECH-4b** | *4b: Double-hop required* | NC | The double hop transfer delay for a GEO solution is not compliant with railway requirements with independence of the frequency band used, since only considering the propagation delay to a GEO satellite is around 500 ms. |
| **CRT-TECH-5** | *Delay jitter of the proposed satcom system shall be Low.*<br>*Note: Since this criterion refers to the one-way satellite channel jitter, it shall be measured from satellite transmitter to satellite receiver.* | C (Low) | Just like previous "opened" GEO satcom solutions, this criterion is marked as a "C (Low)", since there exist mechanisms to compensate the delay time variations between packets at IP level, but the lower the orbit the lower the delay jitter. |

| ***Inmarsat 5 (Global Xpress)*** | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-6** | *Network registration delay for the proposed satcom system shall be Normal (with similar values of current GSM-R system).* | NC | Assuming a good network dimensioning according to the estimated throughput, the registration process of the GEO/Ka-band system based on DVB-S2 / DVB-RCS2 communication standards can take a "normal" time similar to current GSM-R performance.<br>But for the Inmarsat 5 system, and assuming a previous GPS synchronisation required just like the Inmarsat 4 system, the network registration delay could take too long. |
| **CRT-TECH-7** | *The call establishment delay for the proposed satcom system shall be Low.*<br>*Note: as a first reference, GSM-R establishment delays can be considered.* | C | Assuring the correct dimensioning of the network resources according to throughput requirements, Inmarsat 5 (or a GEO/Ka-band "open" system), which is based on IP and DAMA access scheme, can assure a low establishment delay. |
| **CRT-TECH-8** | *The proposed satcom system shall allow (at least) the estimated number of European FRMCS users by 2030 registered simultaneously.* | C | The use of the Ka-band (with lots of spectrum available), along with the TDM/MF-TDMA (DAMA) implementation based on DVB-S2/RCS communications standards, assure the service for the number of users estimated by 2030. In addition, the use of the Ka-band offers the possibility to support extra performance and/or business applications (in addition to the critical ones).<br>GX is able to provide service to more than 500,000 users per satellite. |
| **CRT-TECH-9** | *The proposed satcom system shall provide priority and pre-emption mechanisms.* | C | Since GX is based on DVB-S2/RCS communications standards, they offer priority mechanisms at level 2, providing for example differentiated queues for different types of traffic (real time, critical data, best effort...). |
| **CRT-TECH-10** | *The proposed satcom system shall support Data and Voice services.* | C | Inmarsat 5 is a Packet Switched system supporting voice and data IP services. |

| Inmarsat 5 (Global Xpress) | | | |
|---|---|---|---|
| **Criterion ID** | **Criterion** | **Evaluation** | **Justification** |
| **CRT-TECH-11** | *The proposed satcom system shall support as minimum Low bandwidth applications* | **C (High)** | With the use of Ka-band, Inmarsat 5 (GX) supports broadband applications. It means that critical railway applications are supported. But also some other such as performance and/or business applications can be provided by Global Xpress. |
| **CRT-TECH-12** | *The proposed satcom system for the FRMCS shall provide "user-to-user" and "multi-user" types of communications for both voice and data services. In addition, each communication can be bi-directional or uni-directional with any type of asymmetry between forward and return channels (when bi-directional).* | NC | In general, the user to multi-user communication on the return link (i.e. from the remote terminal point of view) is not a service offered by satcom solutions.<br>In this case, and despite it is an all-IP solution and it could be implemented at IP level, Global Xpress is a "closed" system that does not provide this service and required modifications depends on the satcom service provider (i.e. Inmarsat). |
| **CRT-TECH-13** | *The minimum required coverage of the satcom system shall be Europe.* | C | Inmarsat 5 (GX), with its 3 current satellites (4 in a near future), provides coverage worldwide (excluding poles). |
| **CRT-TECH-14** | *The satcom system shall provide communications for remote terminals when stationary and when travelling at speeds up to the maximum allowable line speed or 500 km/h, whichever is the lower.* | C | GX air interface is based on standards DVB-S2 and RCS2. Mobility extensions have also been considered to support high-speed environments since it provides service to airplanes, as well. |
| **CRT-TECH-15** | *The proposed satcom system shall be flexible to support (at least) new created apps in the future.* | **C (High)** | DVB-S2/RCS2 standards have been designed to provide high level of flexibility with lots of modcods and bandwidth channelization. Since Global Xpress is based on these standards, it can be considered highly flexible. |
| **CRT-TECH-16** | *The proposed satcom system shall be highly and easily scalable.* | C (Low) | The use of the Ka-band provides high level of scalability. In addition, Global Xpress provides additional techniques such as multi-beam and frequency reuse that increase scalability. |

| Inmarsat 5 (Global Xpress) | | | |
|---|---|---|---|
| ***Criterion ID*** | ***Criterion*** | ***Evaluation*** | ***Justification*** |
| **CRT-TECH-17** | *The proposed satcom system shall allow the use of the following types of terminals: "On-board (mobile)", "Handheld" and "Fixed".* | PC | High frequency bands such as Ka do not make possible the use of handhelds. In addition, fixed and on-board terminals shall use directive antennas, making them more complex (and expensive) than low frequency band terminals. |
| **CRT-TECH-18** | *The proposed satcom system shall provide high level of safety in the information exchanged.* | **C (High)** | Global Xpress is based on DVB-S2/RCS2 standards, which can provide techniques for safety purposes, such as diversity, enhanced FECs, fast signal acquisition… Therefore, GX can make use of these mechanisms to provide the level of safety required. |
| **CRT-TECH-19** | *The proposed satcom system shall provide high level of security in the information exchanged.* | NC | Commercial standards such as DVB-D2/RCS2 are not implementing specific functionalities to counteract intentional interferences effects on the L1 and L2. |

Table 63: Inmarsat 5 assessment

### C.11.1 <u>Additional information useful for the assessment</u>

#### C.11.1.1 Delay study

Taking into account the high data rates achievable by GX and the GEO constellation, the main part of the transmission delay will be the propagation delay between terminal and satellite and vice-versa. In fact it is an example very similar to the one performed for the GEO / Ku-band satcom solution. Therefore, and following the same approximation:

$$T_{packet} = T_{tx} + T_{up} + T_{down}$$

Where,

$T_{tx}$ is the transmission time for a given packet

$T_{up}$ is the propagation delay from ground to the overhead satellite

$T_{down}$ is the propagation time from the satellite to the ground

In order to provide an example, following data is assumed:

Data packet: 120 bytes
Transmission in return link: 500 kbps (maximum 5 Mbps)
Transmission in forward link: 2 Mbps (maximum 50 Mbps)

Then, the end-to-end transmission packet delay in return link is:

$T_{tx}$ = packet_size / throughput = 120 bytes / 500000 bps = 1.92 ms

$T_{up}$ = $T_{down}$ = sat_distance / speed = 36000 km / 300000 km/sec = 120 ms

$$\Longrightarrow T_{packet} = 1.92 + 120 + 120 \cong \mathbf{242\ ms}$$

This result shows that the very big part of transmission delay in the GX system is due to the GEO satellite. The data rate could be even greater than the considered one, but transmission delay will not be smaller than the ~240 ms, i.e. the time due to the GEO satellite.

#### C.11.1.2 Inmarsat 5 - Global Xpress link availability example

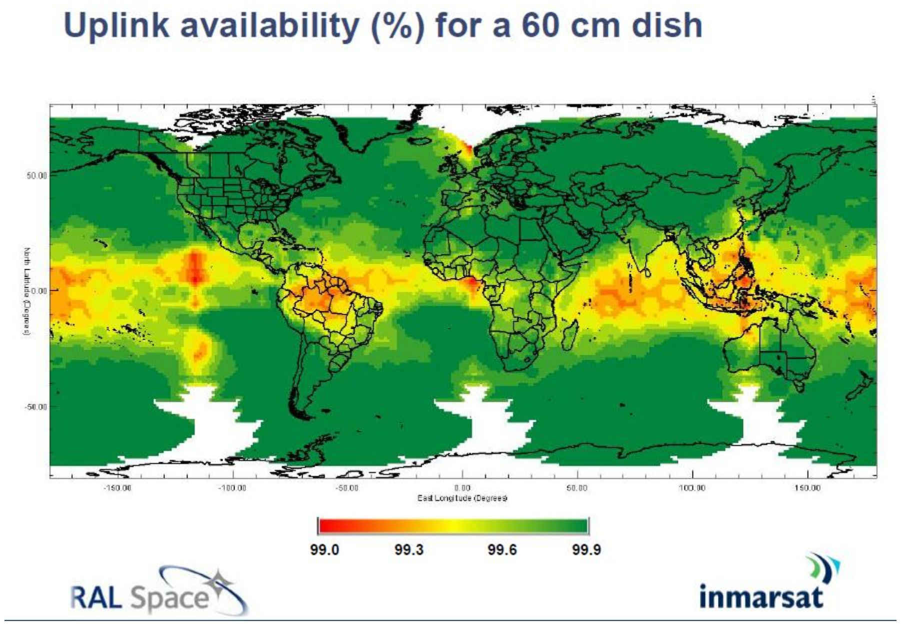


Figure 100: Global Xpress uplink availability (%) for a 60cm dish

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