Annex: Guideline for Choice of Technology

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Executive Summary

This document outlines several factors that have an impact on the choice of technology for a new railway telecommunication system and provides guidance for selecting a communications technology with special focus on the radio access network. The candidate technologies for the Adaptable Communication System (ACS) are 5G, LTE, SatCom, WiFi and GSM-R (whereby GSM-R is the as-is technology). This document provides more technical details and compliments the business model deliverable (D3.2) that looks at commercial implications of candidate network architectures and ownership options.

The focus of this document is to look at factors that determine the technical suitability of candidate communications technologies that may provide a step change in capability compared to that of GSM-R. In addition to the user requirements there are economic and technical drivers and data traffic patterns of the different railway scenarios, i.e. mainline / highspeed, urban/metro, regional, freight. Since communication traffic in relation to the different railway scenarios is an important factor for the choice of technology a calculation tool is provided.

Analysis shows that there is not a single communications technology that fulfils all requirements without drawbacks and so it is apparent that a hybrid of technologies is needed to cover the full range of operating scenarios. It is important to consider the time line of 5G as a future technology as this is the most promising choice, however there are challenges to be addressed in order to utilise its full potential. In terms of a migration strategy, other terrestrial or satellite-based options could be considered for the fulfilling short and medium-term communications requirements.

Factors such as preferred technical and commercial strategies and availability of spectrum will determine which path railway Infrastructure Managers are going to choose for a future communication system. This deliverable provides scenarios that show how the choice of an application with demanding requirements impacts the strategy of technology choice when compared to one with low requirements.

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1. Abbreviations and acronyms

Abbreviation / Acronyms	Description
AMR	Adaptive Multi-Rate
ATO	Automatic Train Control
BTS	Base Transceiver Station
CBTC	Communication-Based Train Control
ETCS	European Train Control System
FRMCS	Future Railway Mobile Communication System
HEVC	High Efficiency Video Coding
IM	Infrastructure Manager
IoT	Internet of Things
MAAP	Multi Annual Action Plan
NaaS	Network as a Service
RAT	Radio Access Technology
RU	Railway Undertaking
URS	User Requirements Specification
WB	Wideband

2. Background

This document constitutes the first issue of Deliverable D3.3 “Specification of the Communication System and Guidelines for Choice of Technology” in the framework of the Project titled “Start-up activities for Advanced Signalling and Automation Systems” (Project Acronym: X2Rail-1; Grant Agreement No 730640). It should be noted that throughout this deliverable 5G is used as an umbrella term, as an enabler of the future-oriented ACS.

This document has been prepared to provide an overview concerning the factors that have an impact on the strategy of technology choice for the adaptable IP communication system. It integrates inputs from other activities in the same WP such as the work on user requirements and the specification of the communication system.

The strategy of technology choice for IMs in the railway context is a complex matter. The available or potential technologies and to what degree they fulfil user requirements are one of (important) components. Different requirements, e.g. data traffic, latency and reliability, of railway scenarios (Highspeed/mainline, urban/metro, regional and freight) provides a more specific view of the suitability of various technologies. A communication traffic analysis has been carried out to have a better view on how e.g. data rates affect the suitability of a technology.

There are other factors which have impacts on the strategy of technology choice. For example, the IM may need to assess and evaluate whether asset ownership is the preferred model and also whether *complete* asset ownership is realistic.

An assessment of technologies is carried out by looking specifically at applications in a given context.

3. . Objectives

Goal of the Task 3.5 within the project X2Rail-1 WP3 is the development of guidelines for the choice of suitable radio access technologies for the implementation of a next generation adaptable communication system. The two main objectives of the task which are detailed in the deliverable are:

1. Analysis of communication traffic, based on a traffic model capturing the needs of the four railway domains (mainline, urban/metro, regional, freight).
2. Development of guidelines for the assessment and the choice of standardised radio access technologies which are suitable for the delivery of railway communication services, especially considering:
    a. Requirements as defined in the preceding deliverable D3.1 “User and System Requirements” [1] ensuring sufficient Quality of Service.
    b. The traffic model analysis.
    c. Existing knowledge on the characterisation of railway environments from a radio link perspective.
    d. Interoperability of terrestrial and satellite-based radio technologies to support the requirements.

The first objective is addressed in Chapter 5 of this document. The results will be used in the Deliverable D3.3 “Business Models” in order to relate technical requirements referring to the necessary infrastructure with cost aspects.

The second objective is addressed in Chapter 4 this document. According to the MAAP [4] the resulting approach is envisioned to be used for the identification of suitable technologies during the prototyping task (described in deliverable D3.4 “Prototype Development Report”). Additionally, it may be employed by railway infrastructure managers for assisting with their own technological assessment.

The selection criteria are defined in this document. The criteria will be linked to candidate radio technologies including LTE, 5G, Wi-Fi and satellite communications. This assessment does not result in the choice of a single technological candidate, but provides a guideline to aid the assessment and selection of both available and emerging radio technologies that address a use case.

4. Economic and Technical Drivers

The implementation of a future communications network for the needs of the railway domain is complex. Apart from technical capabilities, political and economic issues affect a system decision.

Increasing rail traffic, growing requirements for passengers' safety and security as well as providing multimedia information and data access in trains and stations are the main challenges stimulating the next generation of railway communications. These demands result in performance limitations of today's railway communications systems caused by technologies which can no longer cope with these requirements [5].

Table 1 provides an overview of the evolution of various mobile terrestrial transmission technologies according to 3GPP [17] in terms of data rate. (is data rate the only KPI? How about coverage, latency etc. Maybe comment on WHY data rate is the only KPI in the table)

Generation	Mobile Technology	Maximum Data Rate
1G	NMT	12,0 Kbps
2G	GSM	9.6 kbps
2.5G	HSCSD	57.6 kbps
	GPRS	115 kbps
2.75G	EDGE	236 kbps
3G	UMTS	384 kbps
3.5G	HSPA	14.4 Mbps
	HSPA+	42.2 Mbps
3.9G	LTE (up to CAT 4)	150 Mbps
4G	LTE Advanced (LTE-A from CAT&)	300 up to 600 Mbps
4.5G	LTE Advanced Pro (LTE-AP from CAT 11)	1 Gbps

5G	5G network technology	>10 Gbps

Table 1: Generations of mobile technology and comparison of their performance [17]

The deployment of cellular mobile technology started in the 1970s and it is not expected to finish in the near future. The speed concerning the development of new standards has accelerated. As soon as a standard such as 4G reaches market maturity the next mobile technology generation is being defined: Telecommunications technology obsolescence is an important aspect that is not in line with railway system lifecycles. The needs and requirements of future train-to-trackside communications are not supported by today's systems. IMs were not considered a relevant target group in the development process for the consecutive generations of mobile technology.

One of the key impacts of the mobile technology evolution for IMs and RU is the point at which the development path is entered. For example, jumping from GSM directly to 5G has to be reflected in the migration strategy. It should be evaluated to what extent technology evolution is the preferred approach, and to what extent a "big bang" approach with complete substitution of infrastructure offers more advantages.

The following sections refer to the work of MISTRAL which is an open call project of Shift2Rail. They cover essential aspects from economical to technical aspects relevant for the resulting guidelines and recommendations [9][1].

Frequency allocation and spectrum allocation market:

The choice of future radio communication technologies has a crucial role in terms of investment and the choice of frequency. The available spectrum for railway operation can affect the migration to a favoured path. Railway safety and other applications need to have sufficient data capacity. EC has mandated ECC to report on the railway needs and the potential spectrum solutions. It is expected that that the European railways will have 2x5.4 MHz available at 900 MHz and an additional 10 MHz TDD at 1900 MHz. An ECC Decision validating those spectrum scenarios is expected around November 2020.

If adequate frequency spectrum is not available, services taken from a third-party MNO with access to their spectrum assets would be an option for fulfilling the data capacity requirements. In order to shift from GSM-R to a new radio communication technology, co-existence of at least two different communication systems will be needed for a certain period

[1] Please note that reference [9] is currently being modified by Mistral.

of time, i.e., until such time as GSM-R ceases to operate. The frequency allocation influences the financial and socio-economic impact for several of the identified communication scenarios by considering the following two solutions:

1. By using the *same band as GSM-R*, the costs for the licence or for the concession of the spectrum should not increase (given that there are such costs), if the owner of the new infrastructure is the same of the previous one. Additional costs should be considered only in the case of the new owner is different to the old one. Today, the current frequency allocation for GSM-R is dedicated only to the railway sector.
2. Another option would be a *new band*, where a spectrum, that is already devoted to commercial services by telecommunication operators, is assigned to mission critical services. The same applies for a spectrum which is acquired on the market for providing communication services to railways. The last alternative strictly depends on the availability of free frequencies in the market for spectrum. A discussion about spectrum for railways towards future communication technologies is ongoing and still not finally solved. It should be noted that the licencing conditions also determine whether railway companies are allowed to offer passenger broadband services. This does not only have an impact on the business model but also on the selection of equipment. It is be probably unlikely that IMs would be able to afford bidding for commercial 5G spectrum when the profit of additional passenger broadband service is marginal.

State Aids, State incentives, subsidies, etc.:

State governments and the European Union as a whole can play an important role in terms of incentives and the opportunity to finance the investment:

- They could determine a lower price for the allocation of dedicated future railway spectrum (e.g. do not make it part of a frequency auction).
- The state could finance the building of infrastructure but leave the management to the railway IMs.

Regulation:

One of the main drivers for IMs and RUs to migrate towards a new paradigm are the EU regulations (such as the Fourth Railway Package [25]) as well as state laws with their need for technology standardisation and the regulation of interoperability of railway routes.

In addition, regulation is an important aspect for the operation of mobile telecoms network such as 5G. The licence conditions determine whether RUs can offer services to customers such as passengers or logistics companies, or whether only directly railway operation related services are allowed to be supported. This has clear implications for any business case.

Technology Standardisation:

Standardisation usually implies the creation of an EU-wide market, cross-border services and reducing uncertainty of the investments. The process of standardisation requires a consensus from stakeholders and it has impact on the costs for technology providers as well as on the prices for IMs and MNOs. On the one hand, there are policy aspects of standards on railway safety and interoperability (e.g., harmonization of safety requirements EU-wide). On the other hand, standardisation can have positive impact on the price of technology.

Re-use of infrastructure (sites, equipment, etc. of IMs):

The possibility to re-use or sell some components of the legacy communication technology (e.g. GSM-R) can have an important impact on the cost implementation of new communication systems. BTS sites and further equipment such as antennas should be re-used as far as possible in order to decrease cost.

Innovative Services for IMs and for passengers:

With the development of new communication technologies such as those catalysing the emergence of 5G, innovative services and service models can be generated, with IoT based logistics services being one such example. New future use cases such as emergency support applications with video components could be initiated due to high data rate capabilities and extreme low latencies. These services could be applied to supporting railway operations as well as to build up new passenger focussed features and services.

Training and jobs:

A technology shift from hardware infrastructure to software-based networking technology could change the required skills for workers and have implication in terms of costs for new jobs and training.

Service Level Agreements:

Railway infrastructure operators must ensure that the communications network enables safe, secure and reliable applications. The choice of bearer flexibility with support from public network operators requires elaborate Service Level Agreements (SLAs) for service assurance and service availability. Requirements related to mission critical services may be too demanding for public network operators. Identifying SLAs with less strict requirements than those related to mission critical services may be more viable for public mobile network operators. However, it might be commercially risky for the MNOs to fulfil the railway specific requirements and to deliver a service that corresponds with what has been contracted with the railway companies. Fulfilling SLAs for critical railway services are not likely to be covered by “normal” contracts. In order to go beyond speculation, it would be necessary to start the discussion with MNOs specifying risks and mitigations. Although first attempts with a questionnaire approach have not led to any feedback from MNOs other methods to start an exchange of positions should be tested (e.g. interviews).

Procurement Strategy:

The procurement strategy is related both to the cost of spectrum allocation and to the purchasing of technology for IMs as well as MNOs. A choice could be made between a consortium-based approach, e.g., for terminal equipment in terms of economy of scale or a standalone strategy based on the national market. National standards and legal requirements (e.g. provisioning of safety certificates by suppliers) need to be considered, as well as characteristics of the existing infrastructure (is it necessary to replace everything or is partial upgrade possible). The pros and cons of a multi-vendor strategy vs. single vendor strategy need to be considered. Knowledge of relevant market aspects in each segment of the telecommunications network is required.

Recommendation: A thorough analysis of the as-is situation including legal requirements and preferred options for vendor selection needs to be carried out prior to any definition of a procurement strategy.

Geography:

Implementing a new infrastructure should consider other variables like the topography where the new infrastructure will be rolled out. For example, urban regions are quite different to the rural ones in terms of signal propagation and service demand. Moreover, another critical issue linked to the differences between rural and urban areas is train frequency, i.e., this may be two trains per hour vs. 30 trains per hour respectively. Various combinations of landscape topology such as mountains can impede the building of a network infrastructure at low costs. Investment in rural areas is not attractive for MNOs due to the low service demand. Unless new revenue streams are identified it is not likely that they will create a Network as a Service covering such areas.

Recommendation: The impact of the geographical structure on network planning needs to be considered for the deployment of technology such as 5G. Provided that interoperability is possible for the envisaged applications, SatCom may be a viable alternative for areas with low population density; and suitable sight of the sky; suitable latency requirements.

Time

The time necessary for today's IMs to establish an own new network infrastructure should not be underestimated. The main reasons for anticipated delays are:

- IMs experienced in GSM-R have limited experience with network build activities in IP-based networks A shift from GSM-R to 5G is not evolutionary but could be considered a "greenfield approach" from scratch even though BTS and fibre would be available to a certain degree. (The leap of an MNO from 4G to 5G is much smaller than for an IM to go from 2G to 5G)..
- The IM need to acquire personnel that is able to build a 5G network from scratch. Since most vendors follow the strategy to successively enhance LTE networks with 5G components it will not be easy to get sufficient staff with this experience.
- The IM could decide to buy a 5G network "off the shelf" from a telecoms equipment vendor. However, persons experienced in 5G network planning and design are not likely to be competent in railway-related issues. The coordination of the general network aspects and those specific to railway requires time.
- The "telecoms railway infrastructure revolution" would require a learning curve that are likely to be time-consuming and costly. It is unclear how long it takes to reach a satisfactory competence level.
- In order to fulfil the increased traffic demand for future railway services, IMs may need to increase the number and evaluate the suitability of existing sites. The acquisition of new sites is a lengthy process not only because of ownership issues but also because approvals from regulatory agencies takes time. Public MNOs already have a dense network of their own antenna sites and also practice co-location with other NMOs.

Recommendation: Prior to a decision for or against proprietary infrastructure owned by the IM, the necessary pre-conditions (e.g. IMs capabilities and strategic direction) need to be evaluated. In order to come up with a realistic time plan for the ACS migration, pilot tests should be conducted in order to reveal critical aspects in terms of deployment, performance and operation. The build and management of a future-oriented telecommunications network does not belong to the core processes of a railway IM. One alternative is to turn to an MNO for this task. However, for an MNO offering either NaaS or railway services to IMs might not be commercially attractive. One option for a way out of this dilemma could be that the offering of specific railway service types is part of the 5G spectrum licence. The issue of liability in case of failure in meeting SLA conditions could also be addressed in this context.

The MISTRAL consortium has summarised a selection of market trends which are affecting the shift to Network as a Service (NaaS) paradigm as follows [5]:

- Change of requirements due to e.g., new passengers, new jobs, lower environmental impact. NaaS is more flexible in adapting to a changing environment.
- MNOs offering NaaS to RUs may need to increase their network investments in order to satisfy the requirements. They need incentives (financial, or regulatory such as part of licencing conditions) to create a viable offering.
- With NaaS paradigm, MNOs would have the opportunity to invest in a new and unexplored sector (i.e. railway) with new products and/or new business lines, new players entering the market fray (e.g., for external innovative services in the logistics sector). A critical question is whether MNOs are willing to accept the conditions in the SLA and to what price.
- Investment cost for IMs/RUs will decrease in case of change of ownership of infrastructure to commercial operators, hence, it means the goal to minimise costs for IMs/RUs could be reached with NaaS paradigm. Nevertheless, reducing investment costs would not be the only variable that can affect the choice from IMs/RUs point of view to migrate towards a NaaS paradigm. Other relevant issues are safety risks management, policy implications, default risk of existential dependence on a given supplier. [6]

The following KPIs [22, 26] are “maximum expectations” concerning 5G networks. Please note that it is not likely that all targets can be fulfilled at the same time and that there is a variety of different 5G parts and products.

- Capacity: networking between billions of human beings and trillions of things and machines globally
- Latency: between 1 and 5 ms (real time communication for time critical applications)
- Data rate: up to 20 GBit/s downlink and up to 10 GBit/s uplink per cell
- Availability: 99,999% (reliable communication)
- Energy consumption: 10 x less (improved energy efficiency) compared to…
- Networking: Communication directly between terminals, i.e., peer-to-peer communications

The IMs and RU requirements as described in [1] should be evaluated vis a vis these criteria and then compared with NaaS market. For example, outside cities traffic from non-critical services might be off-loaded to an MNO’s network.

Conclusion from economic and technical drivers for the choice of technology: Access to the frequency spectrum is essential for the definition of services. If railway companies have no such access to the required spectrum, they need to turn to public mobile network operators for complimentary coverage and capacity. Apart from cost related aspects, a topic to be discussed with public mobile network operators is whether railway specific services are necessary and can be covered by their business model [9]. Also, the question of who is in control of the services, railway company or MNO, needs to be addressed.

A technical solution such as network slicing requires regulatory agreements that need to be addressed as early as possible

If mission critical applications shall remain under the control of the railway company, a dedicated network infrastructure is one option. As an alternative, the use of the ISM band could be considered [19]. The disadvantages of this part of the radio spectrum such as high interference etc. need to be carefully explored.

If an IMs decides for a limited ownership of infrastructure or does not get the required spectrum the evaluation of different NaaS offerings from terrestrial and satellite operators is a viable option.

Figure 1 provides an overview of some of the main decisions an IM for railway services needs to address when considering what the specific ACS should look like. The starting point is the decision to strive for complete asset ownership or to opt for a hybrid strategy right from the start.

If the decision is in favour of maximum asset ownership steps need to be taken to acquire 5G spectrum and an accompanying license. Even if there is a political decision to grant an IM spectrum there are likely to be obligations that need to be fulfilled. Those conditions need to be evaluated. It is quite realistic that the European railways will get 2x5.4 MHz at 900 MHz and 10 MHz TDD at 1900. However, it is unlikely that any IM would be able to afford bidding for commercial 5G spectrum

In case the license is not granted or not accepted the next step is to revise the strategy and continue with only limited infrastructure (as described in the right-hand side of the diagram).

In case a 5G license is granted the network planning process is intensified. It is an important decision who is responsible for the input to network planning. The IM could rely on their own staff, form a team with a 5G vendor or outsource the whole task. Such a decision has organisational consequences (new staff needs to be hired) and legal implications because of the contract with e.g. 5G vendors, consultants or system integrators. The re-training of own staff may also be considered. The migration strategy needs to be fixed and a time plan has to be established. Reaching Operational Readiness is the final step.

In case it is decided not to bid for a 5G licence a strategic decision concerning network infrastructure is necessary: Should a 5G only network be the goal state or is a hybrid solution a long-term goal. No matter what the result of the decision the next step is the development of a migration strategy. Also, the MNO or MNOs for the realisation of the strategy need to be selected and the process of contract negotiations started. Also, in this case Operational Readiness is the final step.

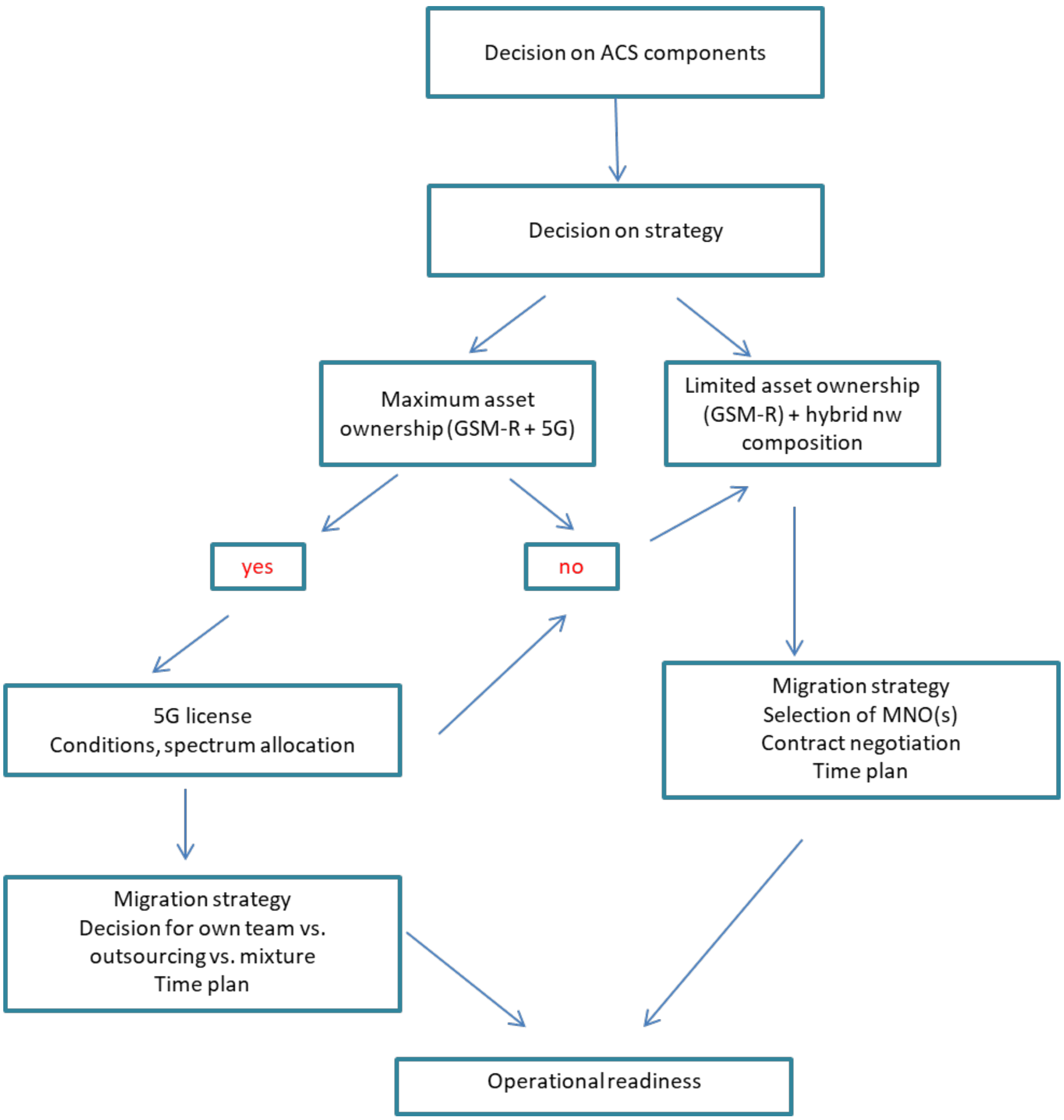

Figure 1: Decision flow concerning 5G infrastructure ownership

It should be noted that the aspect of time is essential for the decision concerning infrastructure asset ownership and all resulting activities. There is a time slot for actions that can be taken to assure an active role in the 5G license process. Also, the decision on what a hybrid network composition could look like needs to be seen in the context of the desired time frame: It is unlikely that a start with a 5G only strategy in 2020 leads to any quick results. Also, a hybrid strategy needs to take into account availability constraints.

4.1. Migration to next generation technology

The predicted obsolescence of GSM-R by around 2030 has led to the European railway community initiating work to identify a successor communication technology and a possible migration strategy. In general, there are different possibilities of co-existence and migration scenarios between existing public and private safety networks and future systems. Currently, different groups like the Future Radio Mobile Communications System (FRMCS) Project or the Working Group Next Generation Radio for Rail (NG2R) are analysing ideas for migration planning of the existing railway communication networks. From the technical point of view several compatible network assets exist and may be re-used within future networks depending on the frequency: the core and backbone network, radio sites, on-board installations (e.g. antennas, interfaces). The existing European framework in terms of rules and interoperability requirements for railway provides fundamental key aspects for migration strategies. The GSM-R successor technology and the migration must guarantee interoperability and roaming as well as bearer flexibility throughout Europe. Migration should be seamless from a communications traffic and service point of view.

The European Rail Agency (ERA) has commissioned SYSTRA to conduct a “Study on migration of railway radio communication system from GSM-R to other solutions” [14]. Within this report, a few general aspects have been considered for the implementation of a complete GSM-R system comprising fixed infrastructure and on-board equipment:

- Vertical integration – i.e. the rail infrastructure is managed by the same entity as train operations
- Size of the national infrastructure
- Size of the train fleet of the different RU’s
- Number of classes of vehicles
- Geographical reach of the various vehicles – what part of the fleets operate cross border and on what rail networks
- Overall project programme constraints
- Deployment of the fixed infrastructure including transmission and fixed telephony
- Availability of vehicles for fitment and testing

- Availability of drivers for testing and training
- Impact of possible train delays (as a result of the implementation of GSM-R) on safety, operations and revenue
- Safety and regulatory regime
- Interoperability with neighbouring rail networks
- Project funding
- Interoperability and interworking between different areas according deployment and bringing into service or even, in some cases, between different IM in a same country

Depending on different countries, the migration timeframe could be longer than 10 years. In terms of costs, it is important to note that the total cost of a migration on an EU scale depends on different characteristics (e.g. age of investment in GSM-R, type of contract and duration for operation or maintenance) of each member state.

The following general migration scenarios could be currently considered:

- Install Dual-Mode (or multi-mode) implementation of GSM-R network and new technology network on specific tracks during a long overlap time (both networks are operated in parallel). On-board equipment on trains has to be exchanged with multi-standard capable devices in advance. Operating and maintaining two technologies in parallel is from an economical perspective less efficient.
- Deploy new network infrastructure in parallel to GSM-R allowing single mode trains fitted with GSM-R or with a new technology to travel over the same line. However, this option seems to be extremely difficult for large networks (in terms of kilometres per train).
- A combination of both mentioned scenarios, which will allow a maximum flexibility, e.g. mixed scenarios like track wise migration with overlap period

The implementation of the actual migration to a Network as a Service approach requires that the hardware prerequisites of the network infrastructure (e.g. sites, RAN) must be available. It seems obvious that in urban regions the expansion of the existing network infrastructure will be much easier than in rural regions. Therefore, it is important to consider different migration concepts or a combination as well. In rural regions, the dedicated network equipment of the infrastructure operators will probably have to remain in operation longer than in cities. Here, capacities can be made available quickly by operators and the existing railway dedicated sites can be dismantled. However, it needs to be considered that the radio site deployment along the railway track is more complex regarding planning and deployment in contrast to public mobile operators. The re-use of existing GSM-R radio sites will likely be an important key aspect for the migration strategy. Another open aspect it the migration schedule, the required progress steps and the planned timeline, which are the main questions towards the replacement process of GSM-R.

Table 2 describes a list of possible migration drivers that can influence the migration strategy:

Migration drivers for IM and RU	**Observations**
Equipment reliability decrease	Over the lifetime of the infrastructure the equipment is likely to degrade resulting in a lower system availability if there is no regular equipment renewal
Increase of maintenance cost	Spare parts become increasingly difficult to source and maintenance contracts become more expensive as newer technologies are promoted by suppliers. Qualified technicians also become harder to find. This is likely to be one of the most important drivers for migration.
Product end of life, end of support for equipment assets	Once a technology is no longer supported by the manufacturers, the cost of keeping these networks increases and the possibility of deploying new equipment on new lines becomes almost impossible. This driver will most impact the migration end date.
Cost reduction	Cheaper and more efficient operation of the infrastructure is one of the main goals for IMs. A new network could be cheaper to install and run than continuing to operate an ageing and soon life-expired technology. This is particularly true if the majority of the civil engineering infrastructure is retained.
Introduction of new services, new applications	A new technology is likely to offer additional services to users and the network operator. For the IM this could mean increasing the efficiency of the network (support more traffic with higher data rates)

EU regulation/certification	Another important external driver for migration could come from new European directives resulting in requirements to migrate to a new system (or even a new frequency band). Member states must transpose and apply EU regulations
Relationship with other plans, e.g. introducing ETCS, new lines, etc.	GSM-R network was a main requirement to develop ETCS 2. As a result, some countries installed GSM-R as a driver for ETCS 2. In case of the future Network Generation (NG), IMs rolling out ETCS level 2 and above will need to investigate the impact of their GSM-R networks. If the design and a particular network is not compatible with a major ETCS deployment (unable to support the additional traffic) one option could be to migrate to a more efficient technology fulfilling the new requirements.
New technology standard and equipment availability	More modern and advanced technologies are constantly being developed resulting in new equipment being available in the general telecoms market.
Other reasons (e.g. national requirements or network infrastructure sharing, etc.)	A particular migration strategy may have specific reasons to migrate away to a new technology, e.g. national government decides to impose/favour. Infrastructure sharing between transport and PPDR Railway Undertakings could be forced to migrate to the new system if an Infrastructure Manager migrates to the new system and switches off the former technology.
New services	As part of a wider digital or economic strategy, the EU may impose requirements for the provision of new services.
Spectrum	Pressure from other radio users such as public mobile phone operators may persuade the EU to migrate railways from the coveted 900 MHz band.

Interoperability	Interoperability is a prerequisite for some applications, and has to be considered for any upgrade.

Table 2: Migration drivers

The introduction of new transmission candidates and the future transition from the current GSM-R technology will take place not later than between 2023 and 2030. This also means that there will be a long time of technology transition. The GSM-R industry has confirmed that technical support will continue until 2030. However, the supplier market of GSM-R technology will noticeably shrink, which leads to a negative trend in availability of the hardware equipment and increasing cost of operation. The impact on mobile devices and specific on-board cab terminals will be a significant cost factor for railways. The migration approach is significant for the shift to new technologies and should be considered as a key variable in terms of costs and technical implications that is transversal.

4.2. Railway scenarios

The predominant four railway transport categories are Highspeed/Mainline, Urban/Metro, Regional and Freight. Based on these four categories, different end user requirements from perspective of Railway Undertakings (RUs) could be captured and defined. Please note that although treated separately, the communication infrastructure for the different scenarios is not separate. In practise, one of the challenges is that mainline/highspeed, regional and freight trains typically share the same tracks and same communications infrastructure

GSM-R technology is mainly deployed on highspeed and mainline tracks across Europe to enable communication interoperability mandated by the Technical Specifications for Interoperability (TSI). At the same time infrastructure managers in some countries are still relying on alternative communication systems based on analogue radio or satellite technology, especially for tracks in regional areas. In areas with high user density or significant traffic demand some operators also use alternative radio systems to overcome radio resource shortage imposed by GSM-R. Since the urban rail domain is usually not concerned with interoperability regulations, it has implemented networks based on TETRA and/or WiFi variants [10]. It should be noted some European regions are generally underserved concerning telecom infrastructure because this investment is considered financially unattractive.

4.2.1. Mainline/Highspeed

Mainline is a track that is used for a high variety of trains and often is the principal artery of the system from which branch lines, yards, sidings and spurs are connected. It generally refers to a route between towns, as opposed to a route providing suburban or metro services. For capacity reasons, main lines in many countries have at least a double track and often contain multiple parallel tracks. Main line tracks are typically operated at higher speeds than branch lines and are generally built and maintained to a higher standard than yards and branch lines. Mainlines may also be operated under shared access by a number of railway companies. Nowadays, interoperability in this kind of lines is achieved; although still have a lagging in technology and performance.

High-speed Rail is a type of rail transport that operates significantly faster than traditional rail traffic, using an integrated system of specialized rolling stock and dedicated tracks. While there is no single standard that applies worldwide, new lines in excess of 250 km/h and existing lines in excess of 200 km/h are widely considered to be high-speed, with some extending the definition to include much lower speeds (e.g. 160 km/h) in areas for which these speeds still represent significant improvements. Given the high speeds of the rolling stock circulating along these lines, the traffic control and signalling system must guarantee maximum safety and reliability. [1]

The key applications are currently voice and data services for the operation on mainline railways. Adaptable future communication systems must be able to support new railway related applications as well as changes and extensions to the current ones. The future adaptable communications system must be capable of supporting operational train speeds up to 500 km/h. [1]

The following applications should be considered:

- Highly reliable and accurate Location Determination System (LDS), based on GNSS and other supporting methods for ETCS levels 2 and 3
- Moving block as specific ETCS3 implementation
- Virtual Coupling
- Monitoring of critical infrastructure and on-train systems
- On-board train integrity
- Real time video streaming applications for automatic reaction to hazards (without extensive buffering)
- Maintenance applications

Communications services which are offered to passengers by public mobile networks (e.g. WiFi in train) could also be considered if the applications are not critical.

4.2.2. Urban / Metro

Rapid Transit Railways, including Urban and Suburban Rail, are a type of high-capacity public transport generally found in urban/suburban areas (Heavy/Light Metro, Subway and Tube). Rapid transit systems are electric railways that operate on an exclusive right-of-way, which cannot be accessed by pedestrians or other vehicles of any sort, and which is often separated in tunnels or on elevated railways. Services on rapid transit systems are provided on lines between stations typically using electric multiple units on rail tracks, although some systems use guided rubber tyres, magnetic levitation, or monorail. Due to the very nature of this type of lines, it is necessary that they have a proprietary high-performance traffic control and signalling system.

Within the typology of Rapid Transit Railways, it can be distinguished between different types of transport [1]:

- Automated people movers (e.g. Airport shuttles)
- Monorails
- Light Transit Rail or Light Metros
- Mass Rapid Transit or Heavy Metros
- Commuter Rails or Sub-urban trains

The urban rail applications that are currently requested by the metro operators and already deployed in many metro lines are split into 3 categories [1]:

1. *Critical applications for metro operators*: mainly the train control and operation, e.g., CBTC, and operational voice communication for operator staff
2. *Non-critical application for metro operators*: mainly the tele maintenance of on-board equipment, the Public Announcement (PA), the Passenger Information System (PIS), the CCTV and the platform TV
3. *Non-critical application for the passengers*: mainly the internet access through WiFi on-board and other passengers' services

4.2.3. Regional

Regional Rail also known as local trains and stopping trains are passenger rail services that operate between towns and cities. These trains operate with more stops over shorter distances than inter-city rail, but fewer stops and faster service than commuter rail. Regional Rail services operate beyond the limits of urban areas, and either connects similarly-sized smaller cities and towns, or cities and surrounding towns. Regional Rail normally operates with an even service load throughout the day, although slightly increased services may be provided during rush-hour. The service is less oriented around bringing commuters to the urban centres, although this may generate part of the traffic on some systems. Other Regional Rail services operate between two large urban areas but make many intermediate stops. [1]

Regional lines sharing most of the requirements for mainline, however, until now legacy solutions based on GSM-R have failed to penetrate sufficiently due to their high costs, that do not justify such investment in relation to the volume of traffic. Moreover, also the performances requested are different from the main lines.

For all such reasons, new models are expected in such scenario. A first significant breakthrough in economic sustainability is represented by the replacement of proprietary, dedicated networks with public mobile networks. The use of such public infrastructure makes it possible to rapidly extend the ERTMS/ETCS benefits where the deployment of dedicated radio infrastructure is too much expensive in terms of both CAPEX and OPEX. Therefore, the adaptable communications system should also consider the use of public networks, based on both terrestrial and satellite communication, as low cost and effective enablers for the rapid deployment of the modern railway applications in such scenario, able to determine a reduction or elimination of any fixed wayside infrastructure in order to obtain benefits in terms of economic sustainability, especially for low traffic lines. [1]

4.2.4. Freight

Freight Rail, which is part of the Secondary Rail, is a type of low-density rail for the transport. It’s normally used for the transport of passengers or goods over long distances usually between multiple regions, crossing geographically harsh environments. The vast majority of the secondary rail lines around the world is often composes by single-track lines with medium or low traffic density and long headways between trains. The lack of cost-effective modern technology means that many of these routes still have outdated safety systems, and/or manual operation. There are two kinds of secondary rail: Secondary Freight Rail and Secondary Passenger Rail. [1]

Key applications for current freight lines are the critical communication applications, necessary for the safe operations of railway, i.e., voice communication for staff (e.g., drivers), emergency calls, as well as data communication for supporting ETCS.

Given the lo traffic characteristic of these lines, the same economic considerations made for regional lines are applicable in this scenario as well as the expectations raised from new business models.

A future adaptable communication system which is able to support higher data rates (and lower latencies) will enable further new applications beneficial for rail freight transport including Automatic Train Operations (ATO) and Internet of Things (IoT) related services for the logistics supply chain. [1]

It should be noted that also today's networks support IoT applications. Coca Cola claims to have started with IoT in their vending machines in the 1980s [23] and freight control in shipping started with Maersk's container tracking in 2012 [24].

Conclusion: The selected migration strategy very much depends on the prioritisation of railway scenarios. The Mainline/Highspeed scenario is the one with the most demanding requirements. Nonetheless, regional or freight lines must not be ignored.

Figure 2 highlights the milestones in the definition of a migration plan. As outlined in the previous paragraphs many aspects influence a migration strategy (from organisational readiness to geographical factors. The migration strategy determines the goals and the final state for all the different railway scenarios. Adding scenarios and selecting applications will increase the complexity of the approach. There are interdependencies, synergies but also possible interferences. Starting with all four scenarios in parallel may lead to a level of complexity that is difficult to master. Therefore, it is advisable to select a primary scenario that offer a sufficient number of benefits.

Once the primary scenario has been selected primary applications need to be identified. Interoperability is mentioned as an exemplary requirement essential for further planning. It can refer to the fall-back solutions on other technologies but may also refer to interoperability between applications The next step is to review the available infrastructure. For example, if LTE is used as a starting point in the migration process IMs have no spectrum license and therefore plan for NaaS. This step implies a review of bearer technologies and could lead to a mixture that is most suitable for supporting the selected railway scenario with the envisaged application. Nonetheless, also the choice of multiple bearer technologies implies limitations in terms of e.g. maintainability. The choice (and availability) of equipment also plays an important role for the migration path. The different factors have an impact on the time plan.

Please note that the arrows to the Urban/Metro and Regional scenario are dotted because they are unlikely to be "first choice".

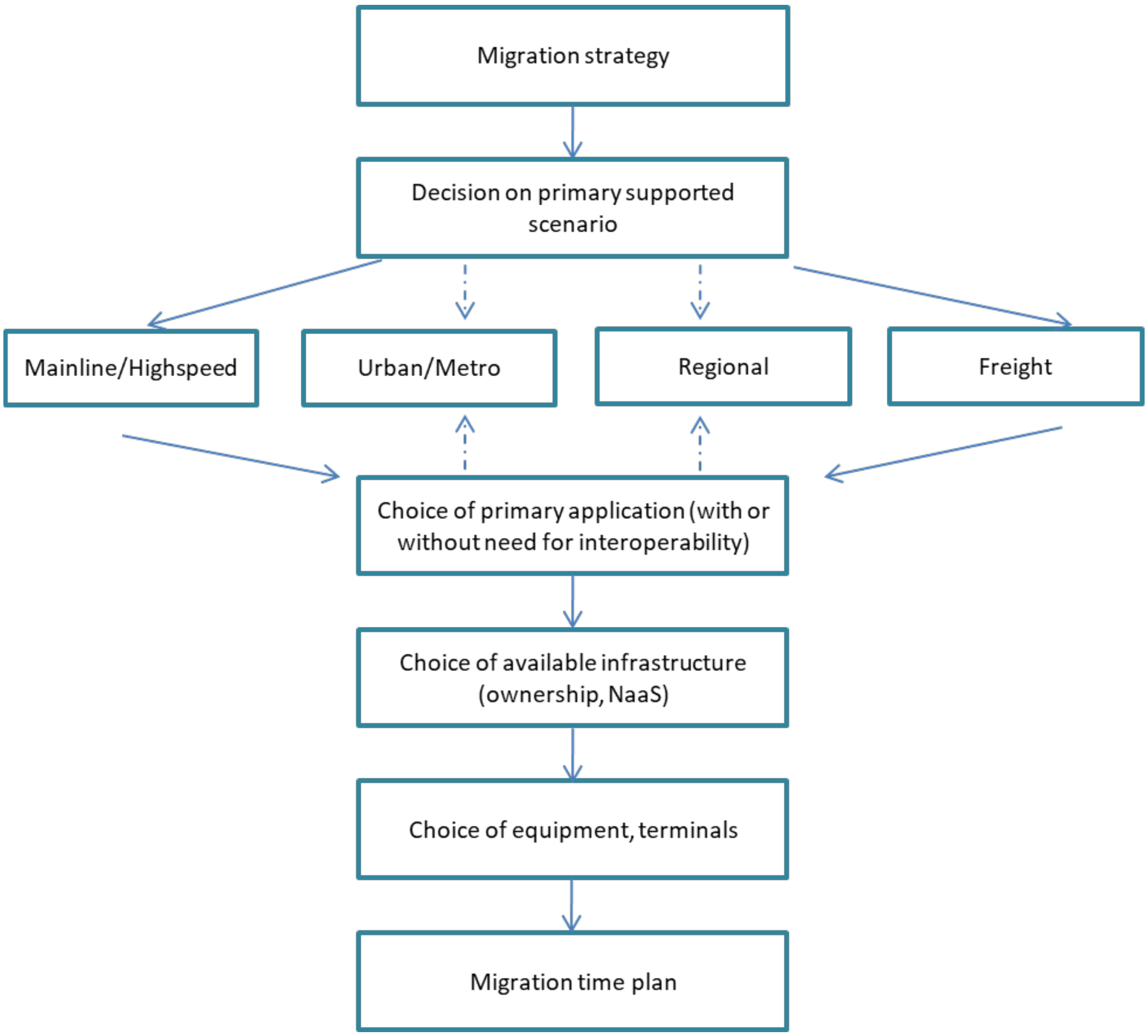

Figure 2: Migration plan decision

5. Communication Traffic Analysis

The overall required data rate is an important criterion for the evaluation of different Radio Access Technologies (RAT) for railway applications. A suitable RAT must provide a data rate that is sufficient to fulfil the need of all applications with the guaranteed QoS. This is particularly important for critical applications. Within the previously published deliverable D3.1 “User & System Requirements” [1], the railway applications have been gathered, along with their high-level requirements and key communications performance requirements. Based on these requirements, a communication traffic analysis was performed in order to estimate the overall data rate that is to be expected in current and future railway communication system. The methodology and the results of this analysis will be detailed in this chapter.

5.1. Methodology

The methodology for the communication traffic analysis is based on the following steps:

1. All applications relevant for current and future railway communication are listed in deliverable 3.1 “User & System Requirements” [1] which serves as an extension of the FRMCS User Requirements [2].

2. Within D3.1 all applications are designated to one of the following categories:
   a. *Critical* applications that are essential for train movements and safety or a legal obligation, such as emergency communications, shunting, presence, trackside maintenance, ATC, etc.
   b. *Performance* applications that help to improve the performance of the railway operation, such as train departure, telemetry, video surveillance for predictive maintenance, etc.
   c. *Business* applications that support the railway business operation in general, such as wireless internet, etc.

3. Within D3.1 [1] all applications were assigned a high-level classification for their required data rate, given as:
   a. *Very Low* with a data rate of up to 5 kbit/s
   b. *Low* with a data rate of up to 50 kbit/s
   c. *Medium* with a data rate of up to 500 kbit/s
   d. *High* with a data rate of up to 5000 kbit/s

   As detailed in Chapter 5.2, for some applications more precise estimates of their respective data rate consumption were made.

4. Based on the definition of railway categories in D3.1 [1], operational parameters (e.g., number of trains per hour) representative for European railway communication were defined for the following generic rail segments:
    a. *Mainline:* A dedicated (high-speed) passenger line / train that spans between cities and possibly across the nations.
    b. *Metro/Urban:* A dedicated urban (mass transit) passenger line / train that spans part or all of a city and possibly as far as the neighbouring towns (with sections both above and below ground).
    c. *Regional:* A remote low-capacity passenger line with few connections that spans between the cities.
    d. *Freight:* A dedicated freight line (no passengers) that spans between the cities and possibly across nations.

    Additionally, a reference train station (including a shunting yard) was considered. The detailed operational parameters used for communication traffic analysis are presented in Chapter 5.2.

5. All communication applications (voice, data, video) are implemented using IP bearers, the associated data rate is expressed in bit/s. For rail segments data rate density is expressed in bit/s/km[i]. As shown in Figure 3, the data rate is estimated separately for downlink and uplink, especially considering the following parameters as defined in deliverable D3.1 [1]:
    a. The uplink-to-downlink ratio (e.g., 50/50 for bi-directional voice).
    b. The frequency of use (percentage of time).

For each application and for each railway category it was decided whether an application was relevant for a given railway category today or whether it would only become relevant for future operations (post-migration). Thus application-dependent traffic growth in the future (< 20 years) can be considered. The future data traffic estimates include also a further foreseeable future growth of 20% (1% per year) [27].

For each application, a data rate per user has been assigned. Then the railway operational parameters were taken into account as well as the frequency of use. Uplink and downlink ratio were also considered. Uplink and downlink data rates were then applied. A decision was made whether the application was relevant for today or for the future. The next step was to consider the growth factor. All this is added up to an overall data rate. Please note that this model still contains simplifications because time factors such as peak or off-peak were not considered. Also, it was not considered that application use is not necessarily happening simultaneously.

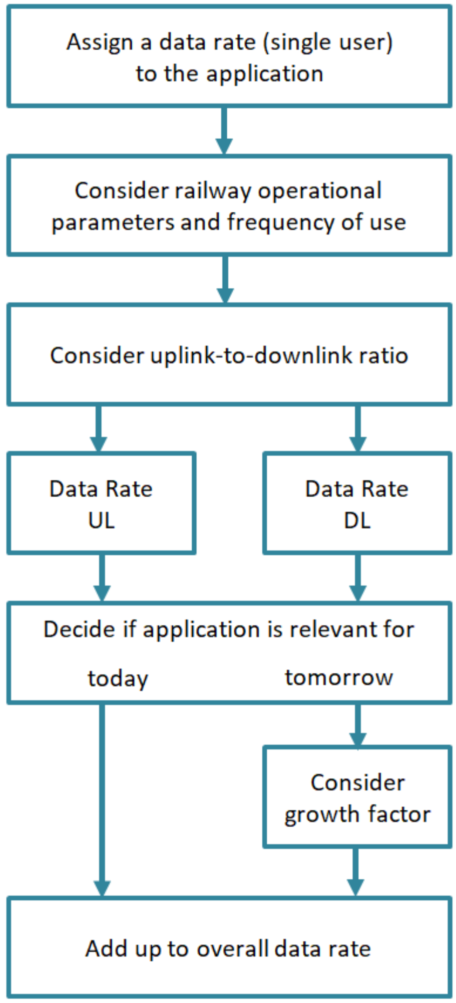

Figure 3: Procedure for communication traffic analysis (for each application)

5.2. Traffic Model Assumptions

Parameters for the communication traffic analysis are listed in Table 3 and Table 4 (railway operation parameters for all four railway categories and the station/yard scenario) as well as Table 5 (application data rates).

For a comparison of different sources for traffic data assumptions please also refer to [31].

Railway operation parameters	Mainline	Metro	Regional	Freight
Maximum number of passengers per train	1000	500	120	0
Average number of passengers per train	400	300	35	0
Average number of staff per train	4	1	1,5	1
Average number of cameras per train	16	18	8	0
Average number of critical cameras per train	2	2	2	2
Average traffic density (trains per hour per direction)	15	30	1,5	1
Maximum train speed (km/h)	500	120	160	120
Average train speed (km/h)	160	80	60	80
Average line length (km)	600	18	250	n/a
Average number of stations per line	12	16	25	n/a
Average distance between stations (km)	60	1,5	15	n/a
Headway (s)	85-240 s	85-130 s	1-2 h	120-240 s
Average number of trains per km	0,5	2	0,33	0,25
Average number of passengers per km	200	600	11,55	0
Average number of staff per km	2	2	0,495	0,25
Average number of on-train cameras per km	8	36	2,64	0
Average number of critical on-train cameras per km	1	4	0,66	0,5
Average number of trackside staff per km	1	2	0,5	0,5
Average number of wayside objects per km	4	8	4	4
Traffic increase due to growth of operations in the future	20%	20%	20%	20%

Table 3 Railway operation for the four railway domains [1]

Railway operation parameters	Station & Yard
Average number of passengers per train	400
Average number of staff per train	4
Average number of cameras per train	16
Average number of critical cameras per train	2
Average traffic density (trains simultaneously active)	25
Average number of trains in station simultaneously active	25
Average number of passengers on trains (total)	5000
Average number of staff on trains (total)	100
Average number of on-train cameras (total)	400
Average number of critical on-train cameras (total)	50
Average number of trackside staff	10
Average number of wayside objects	50
Average number of passengers on platform	2500
Average number of staff on platform	25
Average number of shunters	25

Table 4 Railway operation parameters for the scenario station/yard

Please note that a station is defined as a railway location where a passenger train can start, stop or end. A yard is defined as an arrangement of tracks, other than main tracks, used for making up trains (shunting), storing cars, trains and other purposes [1]. Therefore, one of the key assumptions for this scenario is that there are 25 trains simultaneously active.

Traffic model parameters	average in kbit/s	Comment
Voice	23,85	AMR-WB speech codec, best setting [28]
ETCS	5	Downlink [28]]
CBTC	150	See D3.1 [1]
Video Low Quality	400	medium quality [28]
Video Medium Quality	1250	HEVC video codec, HD, resolution 1280x720
Video High Quality	2500	HEVC video codec, FullHD, resolution 1920x1080
Internet (Passengers)	1128	Average bitrate per train passenger (assuming 500 passengers, 3/4 of passengers online, 1/2 using video application (2.5 Mbit/s), 1/2 browsing (500 kbit/s)).
Internet (Staff)	500	Average bitrate per person assuming internet browsing
Internet (Cargo)	50	
High	5000	Generic value, based on categories defined in D3.1 [1]
Medium	500	Generic value, based on categories defined in D3.1 [1]
Low	50	Generic value, based on categories defined in D3.1 [1]
Very Low	5	Generic value, based on categories defined in D3.1 [1]

Table 5 Data rates for selected applications (calculated according to values from [1]

5.3. Results of Communication Traffic Analysis

The analysis takes into account all applications defined in D3.1 which are essential or anticipated to be essential for railway operation. In other words, the traffic demands from Critical applications and Performance applications (excluding Business applications) are considered in the traffic analysis. Please also compare the figures with those provided by the UIC for FRMCS [30]. For calculating the traffic in a cell, the cell diameter is assumed as 8 meters (typical inter-site distance in current GSM-R networks).

As a result of a detailed communication traffic analysis, the following general observations can be made:

1. The main drivers behind high data rates are video applications.

2. Desired UL data rates surpass desired DL data rates. This is mainly caused by video applications. There is a difference between those video applications with real-time requirements (e.g. ATO) and those without such as CCTV.
3. In the future, voice applications will only account for a small amount of the overall data rate, because voice services will be switched to IP based voice communication. Critical voice services have low bandwidth requirements but QoS requirements for latency and jitter are still high.

In the following sections, the results of the communication traffic analysis are summarised for the four railway categories (mainline, urban/metro, regional, freight) as well as for the station/yard scenario.

5.3.1. Mainline

For the railway category "mainline", results of the communication traffic analysis are summarized in Table 6 (for today) and in Table 7 (for a future, post-migration scenario).

	Critical + Performance
Number of Applications	21
Downlink in Mbit/s per km	0,07
Uplink in Mbit/s per km	0,05
Downlink in Mbit/s per cell	0,56
Uplink in Mbit/s per cell	0,40

Table 6 Data rates for railway category "mainline" (today)

	Critical + Performance
Number of Applications	36
Downlink in Mbit/s per km	2,50
Uplink in Mbit/s per km	6,36
Downlink in Mbit/s per cell	20
Uplink in Mbit/s per cell	50,88

Table 7 Data rates for railway category "mainline" (future, post-migration)

5.3.2. Urban / Metro

For the railway category "urban / metro", results of the communication traffic analysis are summarized in Table 8 (for today) and in Table 9 (for a future, post-migration scenario).

	Critical + Performance
Number of Applications	18
Downlink in Mbit/s per km	5,27
Uplink in Mbit/s per km	50,26
Downlink in Mbit/s per cell	42,16
Uplink in Mbit/s per cell	402,08

Table 8 Data rates for railway category "urban / metro" (today)

	Critical + Performance
Number of Applications	28
Downlink in Mbit/s per km	8,31
Uplink in Mbit/s per km	61,60
Downlink in Mbit/s per cell	66,48
Uplink in Mbit/s per cell	492,8

Table 9 Data rates for railway category "urban / metro" (future, post-migration)

5.3.3. Regional

For the railway category "regional", results of the communication traffic analysis are summarized in Table 10 (for today) and in Table 11 (for a future, post-migration scenario).

	Critical + Performance
Number of Applications	22
Downlink in Mbit/s per km	0,30
Uplink in Mbit/s per km	1,84
Downlink in Mbit/s per cell	2,4
Uplink in Mbit/s per cell	14,72

Table 10 Data rates for railway category "regional" (today)

	Critical + Performance
Number of Applications	22
Downlink in Mbit/s per km	1,44
Uplink in Mbit/s per km	2,45
Downlink in Mbit/s per cell	11,55
Uplink in Mbit/s per cell	19,60

Table 11 Data rates for railway category "regional" (future, post-migration) [30]

5.3.4. Freight

For the railway category “freight”, results of the communication traffic analysis are summarized in Table 12 (for today) and in Table 13 (for a future, post-migration scenario).

	Critical + Performance
Number of Applications	17
Downlink in Kbit/s per km	91,28
Uplink in Kbit/s per km	97,66
Downlink in Kbit/s per cell	730,24
Uplink in Kbit/s per cell	781,28

Table 12 Data rates for railway category “freight” (today)

	Critical + Performance
Number of Applications	26
Downlink in Mbit/s per km	1,27
Uplink in Mbit/s per km	0,73
Downlink in Mbit/s per cell	10,16
Uplink in Mbit/s per cell	5,84

Table 13 Data rates for railway category “freight”

5.3.5. Station & Yard

A station is defined as a railway location where a passenger train can start, stop or end. A yard is defined as an arrangement of tracks, other than main tracks, used for making up trains (shunting), storing cars, trains and other purposes [1].

For the railway category “Station & Yard”, results of the communication traffic analysis are summarised in Table 12 (for today) and in Table 13 (for a future, post-migration scenario).

	Critical + Performance
Number of Applications	27
Data Rate Downlink in Mbit/s	1,63
Data Rate Uplink in Mbit/s	0,96

Table 14 Data rates for railway scenario “station & yard” (today)

Applications	Critical + Performance
Number of Applications	45
Data Rate Downlink in Mbit/s	83,80
Data Rate Uplink in Mbit/s	240,60

Table 15 Data rates for railway scenario "station & yard" (future, post-migration)

The above tables provide a view of applications and different railway scenarios in relation to some of their requirements. They illustrate the relationship between specific environments and their characteristics with users' communication requirements. As a result they can be specified in numeric terms.

An exemplary application of the results of this communication traffic analysis to an RAT assessment can be found in the Appendix.

5.4. Assessment

This chapter provides the building blocks for conclusions concerning the selection of a suitable technology in a specific context.

This chapter illustrates the impact of the context on the general assessment of the suitability of a radio access technology.

The following context-based evaluations have been carried out:

Approach a) is based on railway scenarios and applies the criteria below to Mainline/Highspeed, Urban/Suburban/Metro, Regional and Freight Approach b) applies the criteria below to applications. In both cases the different technologies considered are GSM-R, LTE, 5G, WiFi and SatCom.

The criteria for the assessment are related to those used in the business model. They are defined in Appendix 2: Glossary of the User Requirements deliverable [13] They are defined as follows:

- Capacity: sufficient, insufficient.
- Latency: best effort, normal, low, very low, N/A.
- Bandwidth: High, medium, low, very low, N/A
- Reliability: Very high, high, normal
- Availability: Normal. high
- Maintainability: High, low
- Upgradability: High, low
- Longevity: Yes, no
- Scalability: High, medium, low
- Backward Compatibility: Yes, no
- Resilience to Interference: Yes, no

- Cyber Security: High vulnerability, medium vulnerability, low vulnerability
- Traffic prioritization: Possible, not possible

According to [1], a "low" latency is defined as <100ms. Additionally, "very low" latency is defined as <10ms in this assessment. It should be noted that the criterion "cost" has been left out deliberately because it is difficult to compare the different network types. For example, the cost of GSM-R as such should be low because the network is written off but investment in further equipment might be high. Wi-fI can be used as a complementary access technology but not at the same level as e.g. an LTE RAN. And the cost for a 5G network depends on several factors e.g. the inclusion of costs for the core network or potential license fees.

a) Table 16 provides an overview for the suitability of the different technologies in the Mainline/Highspeed scenario.

Mainline/Highspeed

	Technology	Capacity	Latency	Bandwidth	Reliability	Availability	Maintainability	Upgradeability	Longevity	Scalability	Backward Compatibility	Resilience to Interference	Cyber security	Traffic Priorization
Critical, performance, business applications	**GSM-R**	insufficient	normal	very low	normal	high	high	low	low	low	N/A	yes	high vulnerability	possible
	LTE	sufficient	normal	medium	normal	high	high	high	high	high	no	yes	medium vul	possible
	5G	sufficient	very low	high	normal	high	high	high	high	high	yes	yes	medium vul	possible
	WiFi	sufficient	normal	high	normal	high	high	high	high	high	yes	no	medium vul	not possible
	SatCom	sufficient	best effort	high	normal	high	high	high	high	high	yes	yes	medium vul	not possible

Table 16: General view of fulfilment of requirements for Mainline/Highspeed

It should be noted that the Mainline/Highspeed environment places very demanding requirements on a network. Physical aspects such as train speed have an impact on the suitability of a chosen technology. However, the type of application such as critical, performance or business does not have an impact on the assessment because video based applications have specific QoS requirements, no matter whether there is a critical or a business application. The difference is the impact of QoS degradation. The main impact occurs in case of failure. Wireless technology is more error prone than fixed networks. Therefore, availability and reliability are important criteria. Also, risk mitigation strategies need to be considered such as redundancy redundancy of service components.

There is no weighting of criteria which in some cases might lead to a distorted view. For example, Traffic Prioritisation is only necessary if network capacity limitations are assumed. Although equipment that allows for traffic prioritisation can be installed in IP based mobile networks this is usually done for commercial purposes and contradicts the "discrimination fee access" or net neutrality paradigm. Policy control models based on safety considerations need to be evaluated.

Backward compatibility

The ratings in the table are based on the assumption that LTE is not backwards compatible with GSM-R (it is backwards compatible with UMTS but that is out of scope). It is assumed that the other RATs are backwards compatible with LTE. None is compatible with GSM-R. The conditions for interworking between GSM-R voice and other network types is an item for further study.

Upgradability

The judgement of upgradability is a kind of "within system" comparison. It can mean the shift from LTE to 5G, it can also refer to a more advanced release as in Wi-Fi or SatCom.

Cyber Security

The judgement for cyber security is difficult because to a large degree it depends on the implementation. By today's standards GSM-R is not up to the required standard but the other systems got a "medium" rating because there is no up-front advantage or disadvantage of a system. Table 17 presents the assessment of requirements for Freight trains. Although it is assumed that Mainline/Highspeed has stricter requirements this does not really affect the suitability of the different networks. Relevant aspects are the characteristics of the applications. For example, the train scenario does not matter for critical applications with video components. In terms of network capacity there are differences but they are not relevant because even LTE can be considered sufficient.

Note that the green colour indicates that a technology is particularly suitable for a given scenario type.

There are other criteria which might become relevant when considering NaaS. For example, if an IM decides to use an MNO network the status of the network build activities is relevant. The targets are usually fixed in the national license conditions. For example, in Germany the Bundesnetzagentur has set the target for LTE that in 2019 98% of all cities LTE shall be available (source: http://www.lte-anbieter.info/verfuegbarkeit/lte-verfuegbarkeit-testen.php). This implies that a shift towards a future-proof technology has to be incremental and take into account coverage evolution, particularly in rural areas.

Network Interoperability between networks of different European IMs is another relevant criterion. However, it is not addressed here due to its complexity.

Interoperability topics are particularly relevant in the context of limitations concerning QoS. Not only fallback solutions between 4G and 5G are relevant but satellite communication may play an important role because ground-based coverage restrictions do not apply.

Table 17 shows the Freight scenario as another example. The urban/metro and the regional scenario have been deliberately left out to avoid redundancy.

Freight														
	Technology	Capacity	Latency	Bandwidth	Reliability	Availability	Maintainability	Upgradeability	Longevity	Scalability	Backward Compatibility	Resilience to Interference	Cyber security	Traffic Priorization
Critical, performance, business applications	**GSM-R**	insufficient	normal	very low	normal	high	high	low	low	low	N/A	yes	high vulnerability	possible
	LTE	sufficient	normal	medium	normal	high	high	high	high	high	no	yes	medium vul	possible
	5G	sufficient	very low	high	normal	high	high	high	high	high	yes	yes	medium vul	possible
	WiFi	sufficient	normal	high	normal	high	high	high	high	high	yes	no	medium vul	not possible
	SatCom	sufficient	best effort	high	normal	high	high	high	high	high	yes	yes	medium vul	not possible

Table 17: General view of fulfilment of requirements for Freight

b) In order to arrive at an evaluation that is more clear-cut in terms of guiding the technology choice the criteria were applied to different types of applications in addition to the specific railway scenario.

Table 18 below shows a suitability rating for Automatic Train Operation (including video communication) for Mainline/Highspeed. In order to take into account, the specific requirements for this scenario, the criterion "train Speed" has been added and the criterion "Upgradeability" was removed. If a given technology has a definite disadvantage the cell is marked in red. Hence, it is clear that GSM-R should not be chosen if such a demanding application needs to be supported. The high vulnerability when it comes to security can be seen as a show-stopper.

Automatic train operation (including video communication) Mainline/Highspeed													
Technology	Capacity	Latency	Bandwidth	Reliability	Availability	Maintain-ability	Train Speed	Longevity	Scalability	Backward Compa-tibility	Resilience to Inter-ference	Cyber security	Traffic Priorization
GSM-R	insufficient	normal	very low	normal	high	high	low	low	low	N/A	yes	high vulnerability	possible
LTE	sufficient	normal	medium	normal	high	high	high	high	high	no	yes	medium vul	possible
5G	sufficient	very low	high	normal	high	high	high	high	high	no	yes	medium vul	possible
WiFi	sufficient	normal	high	normal	high	high	medium	high	high	no	no	high vulnerability	not possible
SatCom	insufficient	best effort	high	normal	high	high	low	high	high	no	yes	medium vul	not possible

Table 18: Specific view of fulfilment of requirements for Automatic Train Operation (including video component) for Mainline/Highspeed

In order to show the impact that the application has on the choice of technology table 19 shows the ratings for a simple IoT application. The term “simple” means low data rates, infrequent signals and no criticality in case of errors. In this case no specific criterion was used.

As can be derived from the table, GSM-R can be considered suitable if the security risks appear acceptable. This reflects the reality in today’s IoT market because many applications run on GSM.

Simple IoT application Freight

Technology	Capacity	Latency	Bandwidth	Reliability	Availability	Maintain-ability	Upgrade-ability	Longevity	Scalability	Compa-tibility	to Inter-ference	Cyber security	Traffic Priorization
GSM-R	sufficient	normal	very low	normal	high	high	low	low	low	N/A	yes	high vulnerability	possible
LTE	sufficient	normal	medium	normal	high	high	high	high	high	no	yes	medium vul	possible
5G	sufficient	low	high	normal	high	high	high	high	high	no	yes	medium vul	possible
WiFi	sufficient	normal	high	normal	high	high	high	high	high	no	yes	high vulnerability	not possible
SatCom	sufficient	best effort	high	normal	high	high	high	high	high	no	yes	medium vul	not possible

Table 19: Specific view of fulfilment of requirements for simple IoT application in a Freight scenario

Conclusion: The most suitable choice of technology depends on a number of factors. For example, 5G seems to be the best choice for scenarios with “high end QoS”. Obviously, it is also suitable for scenarios that are less demanding but as can be seen in the example of IoT on freight trains, GSM-R could also be sufficient.

There are constraints concerning e.g. the availability of spectrum, dependencies on the selected business case or even the geographical conditions of specific countries (rural areas, mountains, etc.).

It should be noted that the location factor is very important because dedicated infrastructure in general or 5G in particular might not be a viable solution. In such cases SatCom and other alternatives should be considered.

One of the main factors for the selection of technologies is the strategy and the related time plan of a railway IM. For example, 5G could be selected in a “greenfield approach”. That means little attention is paid to GSM-R as the legacy system or the terrestrial mobile networks of previous generations because 5G fulfils demanding requirements better than the other systems. However, this means that the point of operational readiness for all applications in the different railway scenarios is not likely to be reached in the near future. Also, 5G is a future system in 2018 but before it is fully specified and operationally ready other technologies (6G or disruptive technologies) may have emerged. (LTE as 4th generation system is not yet an “old” technology). The decision may hence imply that the system will become as monolithic as GSM-R.

In contrast, a strategy that is based on evolution could lead to an earlier introduction of less demanding applications and an immediate starting point for the practical learning curve. On the downside it could imply a complex telecoms infrastructure for IMs.

Therefore, when selecting the most suitable technology the primary recommendations is to carefully select all criteria and context variables that are important for an evaluation.

It should also be noted that Internet developments may emerge that are changing what can be expected in future: For example, extremely low latency in combination with high availability, reliability and security will define the character of the Tactile Internet. It will have a marked impact on business and society, introducing numerous new opportunities for emerging technology markets and the delivery of essential public services. This Technology Watch report [25] outlines the potential of the Tactile Internet, exploring its promise in application fields ranging from industry automation and transport systems to healthcare, education and gaming. It goes on to describe the Tactical Internet’s demands on future digital infrastructure and its expected impact on society, concluding with a brief discussion of the role to be played by the ITU framework. Therefore, Tactile Internet may also have an impact on developments in the railway sector. However, this is beyond the scope of the current investigations in the Shift2 Rail project.

6. Conclusions

The aim of this report has been to provide insights concerning the different factors that influence the choice of a given communications technology for delivering the requirements of railway. There is no “one size fits all” choice for RATs (Radio Access Technologies). It depends on several factors such as requirements of applications, traffic models for railway scenarios and last but not least the business model which has been selected. Depending on the chosen model there are more or fewer degrees of freedom in selecting a suitable RAT.

The approach exemplarily visualised in tables 15 to 19 provides a guideline for the type of context that needs to be considered when choosing a specific technology. Technologies are evaluated according to their fit with criteria resulting from user and system requirements. The main determinants are a positive fit of technology for an application in a given railway scenario.

Of course, other criteria like cost also play a dominant role. However, first of all the user and system requirements need to be fulfilled and then cost saving considerations should be applied. Cost related aspects are not in focus of this document but are addressed in more detail in [29].

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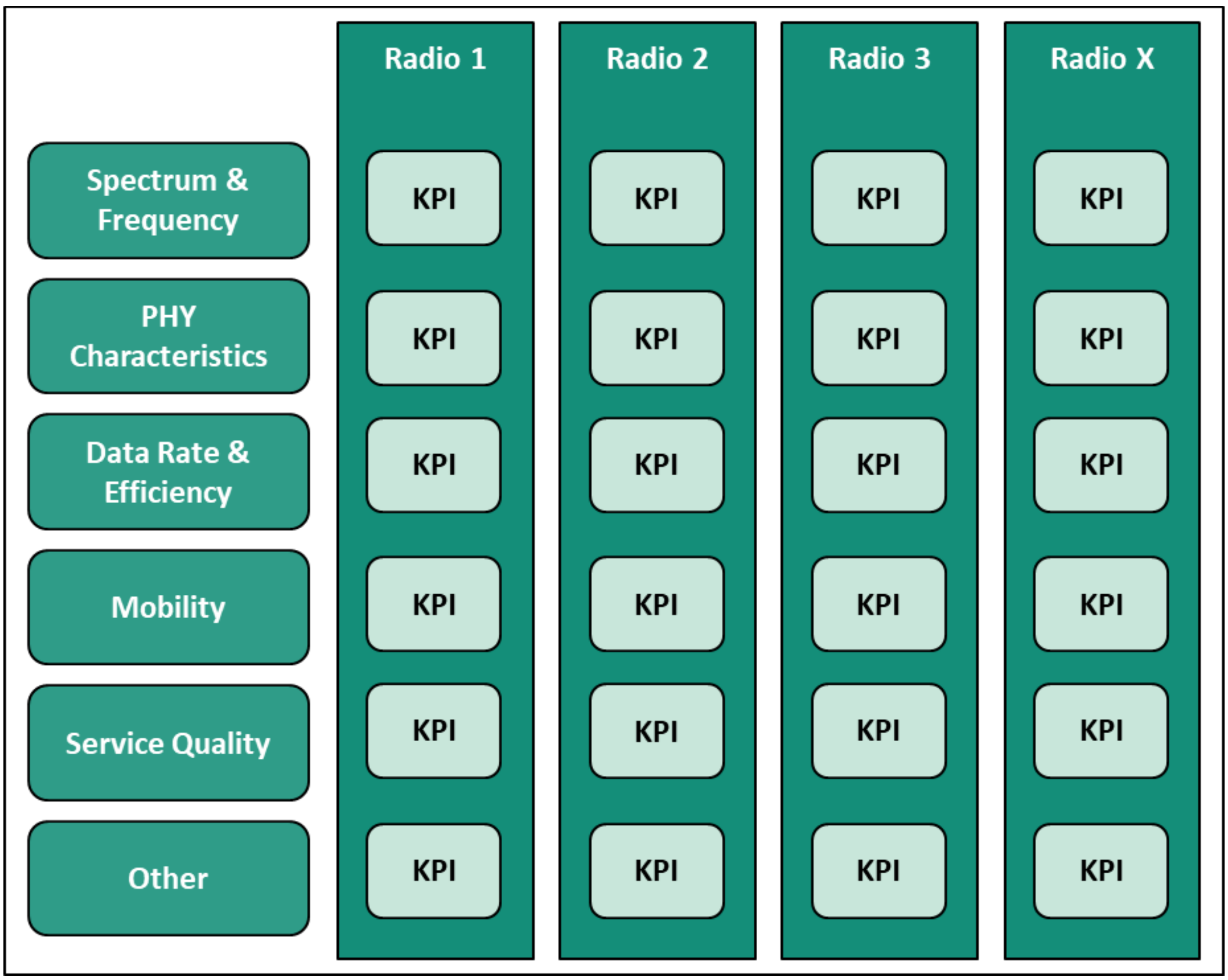
8. Appendix: RAT Assessment Tool

This appendix describes the application of the RAT tool in an exemplary manner. Only GSM-R, LTE and SatCom are described in more detail.

The purpose of the tool is the assessment of different Radio Access Technology (RAT) with regards of their usage for railway communications based on various Key Performance Indicators (KPIs) as well as their communications characteristics.

8.1. Methodology

The goal of the methodology is to keep the modularity and flexibility between different RATs because it is likely that different radio access technologies will coexist.



The key performance indicators have been divided into certain properties such as spectrum & frequency, physical characteristics, data rate & efficiency, mobility, service quality and others like i.e., general support of railway functionality. The detailed list of KPIs is presented in the Excel sheet at the end of this Appendix.

A selected communication technology could be matched against a certain set of criteria, depending on a specific railway scenario (i.e., mainline, metro/urban, regional, freight) or deployment scenario. Minimum requirements can be defined for each KPI with regards the three application categories (i.e., critical, performance, business). For each key performance indicator, it should be selected whether the KPI is merely “informative” or (for critical applications) “obligatory” or “optional”. The output of the assessment is an estimate of whether a specific radio access technology is able to fulfil the requirements of the selected scenario by evaluating the number of KPIs.

8.2. Requirements

User requirements have been ascertained by means of conducting guided conversations with a wide range of railway telecommunication user, stakeholder representatives and have aimed at being as comprehensive as possible, as well as integrating requirements ascertained from the UIC FRMCS project [1].

Five key User requirements (UR) have been distilled, and all the URs have been translated into System Requirements (SRs), i.e. technical performance expectations have been attributed to the qualitative URs and specify the system behaviour and performance level each attribute should achieve for a particular application. These requirements cover the primary use cases for signalling, critical voice, critical video, critical data and passenger connectivity. Key system requirements cover network security risk, mean downtime and availability and encompass mainline, regional, metro/urban and freight rail [10].

- The system will be adaptable in terms of radio access technology support, bearer selection and configuration as required by prevailing QoS demand and availability, and scale in terms of performance, reach and number of users.
- The network will provide a convenient means for migration, upgrade and maintainability, co-existence and backward compatibility when required.
- The network will be able to support safety critical communication for railway applications and be able to provide connectivity to selected third party users, such as primary emergency services.
- The system will be resilient to service disruption through equipment failure, malicious events, interference etc.
- The system requirements should allow for the design of a system that lowers energy and environmental impacts when compared to existing solutions.

8.3. Relevant RAT Technologies

The next communication technology challenges will enhance both the technical and operational aspects of the network capabilities. This evolution seems important to leave an out-dated wireless technology behind and to embrace the opportunities provided by latest IP technologies. [8]

Technological candidates should be able to fulfil virtually all system requirements as captured in the previous requirements chapter (see section 6.2). Generic requirements such as latency, data rate, reliability, availability and adaptability are included, as well as specific functional requirements such as those for voice and voice group calls.

8.3.1. GSM-R

The Global System for Mobile Communications – Rail (GSM-R), is currently used by railway infrastructure managers as well as railway undertakings, for operational voice communications and to provide a data bearer for the European Train Control System (ETCS). GSM-R is essentially the same system as GSM but with railway-specific functionalities. Due to the product modifications required to provide special railway functionality, and the need to utilise non-commercial radio spectrum, much of the equipment utilised for GSM-R comprises manufacturers' special-build equipment and software variant. The use of Modified Off The Shelf (MOTS) technology for GSM-R has proven expensive for the railways, both in terms of capital and operational expenditure. [13]

The predicted obsolescence of GSM-R by 2030, have led to the European Railway community initiating work to identify a successor for GSM-R. The successor has to be future proof, learn from past experiences and comply with railway requirements. In addition to WP3 of the Shift2Rail project the working group for Future Railway Mobile Communication System (FRMCS) has been set up by UIC to identify the railways' needs and defined in a consistent and technology independent way.

8.3.2. LTE

Long-Term Evolution (LTE) is a standard for high-speed wireless communication for mobile phones and data terminals, significantly extending the capability of GSM/EDGE and UMTS/HSPA technologies. It increases the capacity and data rate using a different radio interface together with core network improvements. The standard is developed by the 3GPP (3rd Generation Partnership Project) and is specified in its Release 8 until the current Release 14. LTE is the upgrade path for carrier with both GSM/UMTS networks and CDMA2000 networks. LTE is commonly marketed as 4G LTE, but it does not meet the technical criteria of a 4G wireless service, as specified in the 3GPP Release 8 and 9 document series, for LTE Advanced (4.5G).

LTE offers throughput rates beyond 100 Mbps and a latency of around 20ms. To support this complex functionality, more intelligence must be built into the eNodeB than in its predecessor (3G NodeB). LTE applies the double concept of user-plane (user applications) and control-plane (network control traffic).

The LTE standard covers a range of frequency bands, each of which is designated by both a frequency and a band number. As a result, phones and computerised devices from one country may not work in other countries. Users will need a multi-band capable device for roaming internationally or a specific band clone of the device for a specific country or region [11].

LTE as a typical commercial off-the shelf technology presents multiple advantages for the railway industry compared to the GSM-R solution. The characteristics of LTE (higher bandwidth, significant higher cell capacity, speed improvements) allow it to carry multiple railway applications in parallel. [8] However, depending on the time schedule LTE is likely to be outdated in 2015.

8.3.3. 5G

High-capacity communication networks like 5G (5th generation of mobile networks) will be a key asset for Europe by 2025. The 5G technology with its giga-bit per second data rate is planned to enable industrial transformation in various sectors: 5G should offer data connections above 10 Gbps, latency below 5ms and the capability to exploit any available wireless resources (e.g. from WiFi to 4G). The support of new types of applications connecting devices as well as objects (the Internet of Things – IoT) and versatility, by way of software virtualisation allowing innovative business models across multiple sectors (e.g. transport, health, manufacturing, smart cities) [8].

3GPP continue to work on the specification of critical communications requirements for integration into emerging versions of the 5G standard. This development is of particular interest to the railway sector, as the technical specifications for real safety-critical communication services are carried out here, however the actual time horizon of developments cannot yet be estimated. 5G technology will lead to denser networks, using new spectrum bands with high throughput and shorter ranges – more cells will be deployed, that are smaller and cheaper. They will be using more antennas to increase capacity (Multi Input Multi Output – MIMO approach). Furthermore, the 5G network design benefits from the structural separation of hardware and software, as well as from the programmability offered by Software-defined Networking (SDN) and Network Function Virtualisation (NFV). The architecture is a native SDN/NFV architecture covering aspects ranging from devices, (mobile/fixed) infrastructure, network functions and value enabling capabilities and thus support new multiple use cases and business models [8].

Another type of virtual networking architecture, which belongs to the same family as SDN and NFV, is network slicing. This architecture allows the creation of multiple virtual networks on top of a common shared physical infrastructure. The greater flexibility coming with the network slicing will help to address the cost, efficiency and flexibility requirements imposed by future demands. New service functionalities which weren't possible in previous network communication technologies such as LTE, could be realized by network slicing. Furthermore, the network slicing offers the possibility to meet higher requirements in terms of latency or data rates and in parallel exploit a common network infrastructure [5].

The advent of 5G technology will enable such use cases as high-definition video, automated vehicles and many more future-world services. The following listing the most 5G research and focus on technologies which will help to enable the future-word services.

- Massive Multiple input, multiple output (MIMO)
  5G technology enables base stations to support many more antennas than 4G base stations. With MIMO, both the source (transmitter) and the destination (receiver) have multiple antennas, thus maximizing efficiency and speed. MIMO also introduces interference potential, leading to the necessity of beamforming [https://www.sdxcentral.com/5g/definitions/5g-technology/]
- Beamforming
  Beamforming as applied in 5G technology finds the most efficient data-delivery route to individual users. Higher-frequency antennas enable the steering of narrower transmission beams. This user-specific beamforming allows transmissions both vertically and horizontally. Beam direction can change several times per millisecond. Beamforming can help massive MIMO arrays make more efficient use of the spectrum around them. [https://www.sdxcentral.com/5g/definitions/5g-technology/]
- Millimetre waves
  Millimetre waves are broadcast at frequencies between 30 GHz and 300 GHz, compared with the bands below 6 GHz used for 4G LTE. The new 5G networks will be able to transmit very large amounts of data – but only a few blocks at a time. Although the 5G standard will offer the greatest benefits over these higher frequencies, it will also work in low frequencies as well as unlicensed frequencies that WiFi currently uses, without creating conflicts with existing WiFi networks. For this reason, 5G networks will use small cells to complement traditional cellular towers. [https://www.sdxcentral.com/5g/definitions/5g-technology/]
- Small Cells

Small cells are low-powered portable base stations that can be placed throughout cities. Carriers can install many mall cells to form a dense, multifaceted infrastructure. Small cells low-profile antennas make them unobtrusive, but their sheer numbers make them difficult to set up in rural areas. As 5G technology matures, consumers should expect to see ubiquitous 5G antennas, even in their own homes. [https://www.sdxcentral.com/5g/definitions/5g-technology/]

- Network Functions Virtualization (NFV)
  NFV offers a new way to design, deploy, and manage networking services. Essential to 5G research is the fact that NFV decouples the network functions – such as network address translation (NAT), firewalling, intrusion detection, domain name service (DNS, and cashing, to name a few – from proprietary hardware appliances so that they can run in software. [https://www.sdxcentral.com/5g/definitions/importance-5g-research/]
- Software Defined Networking (SDN)
  SDN and network functions virtualization (NFV) are considered the foundation for how 5G will be deployed. Whereas today's network hardware integrates both the control and data planes, 5G research incorporates the notion of separating these planes. This separation allows network equipment to be externally configured through independent management software, thereby improving flexibility, facilitating centralized control, and ensuring easy network slicing. [https://www.sdxcentral.com/5g/definitions/importance-5g-research/]
- Spectrum Sharing
  Shared and unlicensed spectrum will permit 5G networks to offer greater capacity, better spectrum utilization, and unique deployment scenarios. A key takeaway from 5G research is that spectrum sharing will allow mobile operators with licensed spectrum as well as those without licensed spectrum to take advantage of 5G New Radio (5G NR) technologies. [https://www.sdxcentral.com/5g/definitions/importance-5g-research/]
- Full duplex
  Full duplex communication is a way to potentially double the speed of wireless communication. By employing a 5G full duplex scheme on a single channel, only one channel is needed to transmit data to and from the base station, rather than two. A potential drawback of full duplex is that it can create signal interference. [https://www.sdxcentral.com/5g/definitions/5g-technology/]
- New air interface
  Another 5G principle is being able to manage a "fabric" of networks, e.g. incorporate WiFi as part of the solution. This has required innovations in how the 5G network "core" is engineered

BA: It would be informative to add to each of the above a commentary on how each maps onto Railway communications! Maybe we need to “brainstorm” this in a small group. For some, it is obviously limited.

8.3.4. WiFi

WiFi technologies provide train to wayside broadband connectivity based on a modified version of the IEEE802.11 suite of wireless standards. Most deployments provide broadband connectivity only to railway’s on-board connectivity to passengers, and some to remote control and maintenance services for railways.

WiFi is based on a widely used public standard designed to enable predominantly office and home networking. It is focused to ensure high bandwidth, high data rate transmissions for the transport of long frames of data packets and files on a “best effort” basis.

The 802.11b and 802.11g wireless networking standard use the 2.4 GHz ISM (industrial, scientific and medical radio bands) band, operating in the United States. Due to this choice of frequency band, 802.11b and g equipment may occasionally suffer interference from microwave ovens, cordless telephones and Bluetooth devices. 802.11b and 802.11g control their interference and susceptibility to interference by using direct-sequence spread spectrum (DSSS) and orthogonal frequency-division multiplexing (OFDM) signalling methods, respectively. 802.11a uses the 5 GHz U-NII band, which, for the majority of the world, offers at least 23 non-overlapping channels rather than the 2.4 GHz ISM frequency band offering only three non-overlapping channels, where other adjacent channels overlap. Better or worse performance with higher or lower frequencies (channels) may be realized, depending on the environment. 802.11n can use either the 2.4 GHz or the 5 GHz band together with mimo technology; 802.11ac uses only the 5 GHz band.

In Europe or Japan, the 2.4. GHz band is also free for use, but precise check has to be carried out for each channel used as there may be differences among individual countries, even in Europe. European standard EN 301 893 covers 5.15 – 5.725 GHz operation [11].

8.3.5. SatCom

Satellite communication (SatCom) defines transmission between two or multiple ground stations, via satellite. The integration of the SatCom based solutions with railway applications are part of more complex systems. Satellite communication networks are usually proprietary solutions by satellite telecommunication operators, e.g. Intelsat, Eutelsat or Inmarsat [8].

Depending on the frequency SatCom technology must deal with different impairments and limitations: usually a line of sight connection is required, hence, it can suffer from shadowing of e.g. buildings, at higher frequencies the transmissions becomes rain sensitive. Depending on the orbit, SatCom introduces a significant propagation delay, which impacts real-time applications. But SatCom can be combined with a terrestrial technology inside a multi-vector architecture [8]. SatCom networks are recommended to increase coverage and availability, particularly in low-traffic regional areas, where the implementation of a terrestrial network coverage is not always economically sustainable. The main advantages from SatCom come out from the synergy with the terrestrial networks: SatCom can be combined with a terrestrial technology inside a mulit-vector architecture as demonstrated by in several applications already operational in Australia, Mozambique and USA.

SatCom systems are typically classified by the orbit. The most important one for communication satellites are:

- GEO, geo-stationary (fixed over ground), in orbit of 36.000 km altitude. (Civil) Frequencies are in L-, S-, C-bands (from 1 to 8 GHz), and in Ku- and Ka-band (from 12 GHz to 40 GHz)
- MEO, which means Medium Earth Orbit, between 5.000 and 20.000 km altitude range. Navigation satellites (GPS, GLONASS, Galileo) belong to that class.
- LEO, low earth orbit, between 500 – 1.700 km altitude range. A big number of very mobile satellites are required for a global coverage for scenarios with low latency.

Depending on the scenario and frequency used, pointing antennas are required for the connection which makes the receiver system quite complex. This is the case for mobile users at higher frequencies. Inmarsat, Thuraya from GEO and Iridium SBD offer commercial L-band (1-1.8 GHz) services. Two of them are already used for railway communication:

- The AutoHaul – Rio Tinos's fleet, in Australia, is operating an unmanned (fully autonomous) train, linking 16 mines to four port terminals, using a multi-vector communication solution that include the satellite bearer and Inmarsat service in L-band [16].
- Specific mainline railways have experiences with GEO in L und Ku bands (12 – 18 GHz),
- Inmarsat-Aero (L-Band) is currently used by Aeronautics, and Intelsat GEOs support services for flight passengers in Ku band.

In order to fulfil the Railway requirements, the feasibility of receiving equipment at a low-cost production is highly important. An L-band antenna system has been already defined to guarantee the performance under railway conditions (vibrations, tracking speed, multipath, fading). L-band mobile terminals appear quite expensive.

Wireless radio access bearers may become completed by satellite-based radio. Two options are currently foreseen either satellite may be used as direct radio access by the mobile it will serve as backhaul of the base stations of the land mobile network.

Being SatCom a public network, the ground infrastructures are managed by the providers, in particular, communication managing and controls are in dedicated ground stations. With MEO and LEO, there are switching and managing facilities on board of the satellite. It is a) difficult and b) out of scope to change anything since e.g. a LEO constellation is under the control of USA and characterises as an In-Orbit Infrastructure (IOI) [8].

8.4. RAT Evaluation

Table 20 provides an overview of the approach to the RAT evaluation based on KPIs.

8.4.1. 5G

With the introduction of the 5th generation mobile network, a fundamental change in core network architecture will take place. The networks will enable a fully mobile and connected approach. These new concepts will also be a necessary fundament to build communication networks for railway applications with their own specific higher requirements in the context of a Network as a Service approach. In particular there will be a shift of network architecture from the current network of entities architecture to a network of capabilities architecture. The concept of Network slicing is a way to meet the requirements of all use cases using a common network infrastructure [5].

8.4.2. SatCom

Satellite Communication can be considered as a complementary communication service, because, the availability of such communication vector cannot be guaranteed in all the situations. The use of SatCom is especially recommended to extend and/or increase the coverage and availability in low-traffic regional/freight areas, where the implementation of a terrestrial network coverage is not always economically sustainable Nevertheless, Railway infrastructure managers need to explore available options for envisaged scenarios with satellite communication providers. [8].

The following information has been taken from a final report of the "Study on feasibility of SatCom for railway communication", which has been conducted by Indra and ALG for the European Agency for Railways [15]. However, it worth to remark that they are based on the current technology offer, and do not consider the expectations deriving from the development trend expected in the near future.

The most demanding criteria for SatCom solutions are:

- Availability for critical applications
- Transfer delay between SatCom remote terminals

- The use of handhelds (considering classical voice communication)

Current SatCom services and products, as the only mean of communication, do not fulfil the all requirements for critical, performance and business applications. In particular, SatCom voice services for railways that are considered critical such as voice communications between train and ground (controller), group calls, railway emergency communications, shunting voice communications or public emergency calls do not fulfil the desired QoS.

IP based voice applications add more constraints to SatCom systems for several reasons:

- If pedestrian users are to be supported, handhelds are required that support more than one bearer technology..
- Throughput required by voice applications is much higher than the one required by data applications (current GSM-R situation), 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 system require double-hop for voice calls between SatCom terminals. The delay in this case discards GEO solutions.

Therefore, according to current technology, it is recommended to use satellite technologies mainly for the transfer of data in order to avoid the voice limitations. Hence, solutions technically compliant with railway criteria shall be updated in order to comply with these future established regulations.

In addition, final equipment to be used for railways shall be homologated by satellite operators, in order to control, e.g. the maximum permissible level of off-axis, which depends on the antenna design and is related with the interferences generated to other satellites.

However, the satellite communication networks are not fully standardized. These are proprietary technologies, which coexist with de-facto standards from global satellite telecommunication operators. Although Satellite Communication could be considered as a complementary communication service, the requirements on the availability of the communication vector are quite difficult to realize.

The use of communication standards is also of high importance, since this feature allows many manufactures to provide competitive solutions. Some of the main SatCom standards include annexes about how to implement SatCom On The Move (SOTM) solutions, and even how to implement commercial SatCom solutions for the railway domain are introduced on such annexes.

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 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 profitable. On the other hand, 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.

The use of SatCom in railways implies the adaptation 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. Final design of the antenna and the other equipment shall comply with current railway and SatCom regulations.

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 filed and in a multi-technology architecture.

Despite the current difficulties and limitations, the future will offer increasingly more interested solutions that will bring significant new features and benefits. Among these, it is worth mentioning:

- The use of Software Defined Radio (SDR) based terminal. In this field ESA is about to launch an initiative to define a “Satellite air interface for railways control systems” in order to allow easier definition of the waveforms to be used in the SDR terminals and to guarantee interoperability with different SatCom systems
- The imminent start of impressive launch programs for new generation of low-orbit satellites (LEU) that will guarantee very high performances and offering very low service costs. One of the best known is that of OneWeb that is promising a global constellation of 882 LEU satellites and 42 ground network gateways around the globe, with lowest latency (<50 msec), highest throughput (450 Mbos Down/Beam and 100 Mbps Up/Beam), smallest High-performance User Terminal (30-65 cm), and a system capacity of about 7 Tbps. The frequency operating OneWeb are Ku-band for user links and Ka for gateway links. One of the most interesting characteristics is the Multiple Local Access Options (WiFi, LTE, Ethernet, etc.)

In the future architecture, it is expected to have services and applications independents of bearers. Several new elements or services will arise, such a smart router capable to execute vertical handovers, or even new services are capable to keep connections and their quality of service regardless of the transport network used, as IP Multimedia Subsystem 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).

KPI Input for different RATs

	KPI / Requirement	Description	Link to KUR	Units	Values	Max / Min	GSM-R (GPRS) Values	GSM-R (GPRS) Remarks	LTE (R8) Values	LTE (R8) Remarks	LTE-A (R12) Values	LTE-A (R12) Remarks	5G (R15) Values	5G (R15) Remarks	SatCom Values	SatCom Remarks
Frequency	Frequency Band			MHz	text		876-880 / 921-925		700, 900, 1800, 2100, 2600		700, 900, 1800, 2100, 2600		600, 700, 800, 900, 1400, 1800, 2100, 2600, 3.3-4.2 GHz, 4.4-5 GHz, 26.5-29.5 GHz, 24.25–27.5 GHz, 37-40 GHz			
	Support of GSM-R band				yes / no		yes									
	Use of paired / unpaired spectrum			NN	paired / unpaired / both		paired		both		both		both			
	Channel Bandwidth			MHz	text		0.2		1.4, 3, 5, 10, 15, 20		1.4, 3, 5, 10, 15, 20		100 MHz, 400 MHz	100 MHz below 6 GHz 400 MHz beyond 6 GHz		
	Possibility of Carrier Aggregation				yes / no		no		No		yes		yes			
	Maximum Aggregated Bandwidth			MHz	numerical		0		N/A	up to 100 Mhz in R10	100	in R13 up to 640 MHz	1600 MHz, 6400 MHz	1600 MHz below 6 GHz in 3GPP RAN1 - Physical layer (3200 MHz in RAN2 - MAC layer) 6400 MHz above 6 GHz (12800 MHz in RAN2)		
	Typical Freqeuncy Re-Use				text		1:3		1:1		1:1		1:1			
PHY Characteristics	Transmission Transfer Interval (TTI)			ms	numerical	max	20		1		1		1	(< 1ms)		
	TTI Bundling				yes / no		no		yes		yes		yes			
	Downlink Multiple Access				text		TDMA		OFDMA		OFDMA		OFDMA			
	Uplink Multiple Access				text		TDMA		SC-FDMA		SC-FDMA		OFDMA/SC-FDMA			
	Duplex Mode				FDD / TDD / FDD & TDD		FDD		FDD & TDD		FDD & TDD		FDD & TDD			
	Support of Hybrid ARQ				yes / no		no		yes		yes		yes			
	Support of Incremental Redundancy				yes / no		no		yes		yes		yes			
	Support of Adaptive Coding & Modulation				yes / no		no		yes		yes		yes			
	Support of MIMO				yes / no		no		yes		yes		yes			
	Support of Dynamic Scheduling				yes / no		no		yes		yes		yes			
Data Rate & Throughput	Peak Downlink DataRate			Mbit/s	numerical	min	0,08		150	2x2MIMO, @20 MHz	4000		25000			
	Peak Uplink Data Rate			Mbit/s	numerical	min	0,08		75	@10 MHz	1500		13600			
	Peak Downlink DataRate @ 5MHz			Mbit/s	numerical	min										
	Peak Uplink Data Rate @ 5MHz			Mbit/s	numerical	min										
	Peak Downlink Spectral Efficiency			bit/s/Hz	numerical	min										
	Peak Uplink Spectral Efficiency			bit/s/Hz	numerical	min										
	Average Throughput Cell Center @ 5MHz			Mbit/s	numerical	min										
	Average Throughput Cell Edge @ 5MHz			Mbit/s	numerical	min										
	Guaranteed Minimum Throughput Cell Center @ 5MHz			Mbit/s	numerical	min										
	Guaranteed Minimum Throughput Cell Edge @ 5MHz			Mbit/s	numerical	min										
	Average Spectral Efficiency (Railway)			bit/s/Hz	numerical	min										
Mobility	Maximum Supported Speed			km/h	numerical	min			350							
	Measures against Doppler				yes / no				yes	reference signals / preambles	yes	reference signals / preambles				
	Measures against multipath propagation				yes / no		yes	tail bits	yes	cyclic prefix	yes	cyclic prefix	yes			
	Railway-compatible propagation profiles				yes / no											
Additional KPIs from SRSdoc	Minimum User Plane Latency			ms	numerical	max	600		10		10		1			
	Connection Setup Time			ms	numerical	max										
	Connection Setup Sucess Rate			ms	numerical	max										
	Connection Drop Rate			%	numerical	max										
	Packet Error Rate			%	numerical	max										
	Packet Transfer Delay / Latency			ms	numerical	max										
	Handover Latency			ms	numerical	max										
	Handover Sucess Rate			%	numerical	max										
	Jitter			ms	numerical	max										
Others	Supports interoperability to GSM-R				yes / no		yes									
	Interference with others in same band				yes / no		yes	broad band radio signalling from mobile operators causes interference for GMS-R terminals. Can be handled by	yes	during migration, if done in the harmonized UIC and ER-UIC bandor in the proposed "squeeze option", FRMCS using LTE technology will be interfered by GSM-R or other narrow band signals.	yes	during migration, if done in the harmonized UIC and ER-UIC bandor in the proposed "squeeze option", FRMCS using LTE technology will be interfered by GSM-R or other narrow band signals.				
	Interference with others in neighboring bands				yes / no		yes	to be investigated		to be investigated		to be investigated				
	General support of railway functionality				yes / no		yes	"R" features								

Table 20: KPI Input for different RATs

[i] It should be noted that for the SatCom part it is quite difficult to assess a good system fit based on bits/s/train since usually the density is given over an area (m^2).

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