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User and functional specifications for multi-purpose resilient adaptative on-board telecom networks

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1. Executive Summary

Train services is mainly composed of two main areas namely Train Control and Monitoring System (TCMS) and On-board Multimedia and Telematics (OMTS). TCMS is responsible of the integration of train functionalities such as braking, commands and others. Whereas OMTS conveys users and operator information. Telecommunication infrastructure used by Train Communication Network (TCN) to convey the train traffic is currently very simple and based on a wired system. Due to cables maintenance and diagnosis cost, the efficiency of this system should be greatly improved to enhance the functionality of both TCMS and OMTS domains.

Hence, the New Generation Train Communication Network (NG-TCN) has emerged as a major innovation introducing a wireless architecture as an enabler to enhanced automation, flexible train management and increased railway capacity, in addition to leveraging the virtual coupling concept. NG-TCN targets replacing completely or partially the wired communication infrastructure by wireless solutions and technologies.

However, many challenges lie ahead in the NG-TCN migration, such as the various train types, the diverse environments that the train circulates in and the different requirements needed. In addition to the conventional wireless communication challenges like the uncontrolled interferences, the unstable data rate, latency and coverage distance, not mentioning the security threats. Furthermore, wireless solutions need to be adapted to the peculiar railway environment.

We aim in this deliverable to tackle the NG-TCN emerging challenges by identifying the system user needs and the potential NG-TCN implementation scenarios. In addition to proposing a work methodology to realize the NG-TCN concept in the future railway system and to survey the potential candidate wireless technologies that might meet the NG-TCN requirements. Also, to perform a comprehensive performance comparison study in order to choose the suitable technology/technologies for the future train communication network.

2. Abbreviations and acronyms

Abbreviation / Acronym	Description
3GPP	Third Generation Partnership Project
CCTV	Closed Circuit Television
CN	Consist Network
COS	Customer Oriented Service
CS	Consist Switch
D2D	Device to Device
ED	End Device
EDS	End Device Safety
eNodeB	Evolved Node B (LTE base station)
ETB	Ethernet Train Backbone
ETBN	Ethernet Train Backbone Node
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics
ISM	Industrial, Scientific and Medical
ITS	Intelligent Transport System
MAC	Medium Access Control
MIMO	Multiple Input Multiple Output
MBL	Mobility Load Balance
MRO	Mobility Robustness Optimization
NR	New Radio
ProSe	Proximity Services
SC-FDMA	Single Carrier Frequency Division Multiple Access
SHARP	Synchronous and Hybrid Architecture for Real-Time Performance
SIL	Safety Integrity Level
SON	Self-Optimization Network
TBN	Train Backbone Node
TCMS	Train Control Monitoring System
TCN	Train Communication Network
TDMA	Time Division Multiple Access
LTE	Long Term Evolution
UWB	Ultra-Wide Band
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
WAP	Wireless Access Point
WCN	Wireless Consist Network
WED	Wireless End Device
WEDS	Safe Wireless End Device
Wi-Fi	Wireless Fidelity
WLCN	Wireless Consist Network

WLTB	Wireless Train Backbone
WLTBN	Wireless Train Backbone Node
WTCMS	Wireless Train Control Monitoring System

3. Background

3.1. Project Description

The so-called WIN4TRAIN initiative was created/developed within Task 6.4.1 conducted by SNCF within the WP6. The global aim of the task is to define a multi-purpose resilient adaptative wireless onboard telecom network. WIN4TRAIN will focus on the technical and scientific objectives of the designing and the evaluation of a safe, secure, resilient and versatile wireless solution for train-to-train (inter-consist and intra-consist) communications as illustrated on Figure 1.

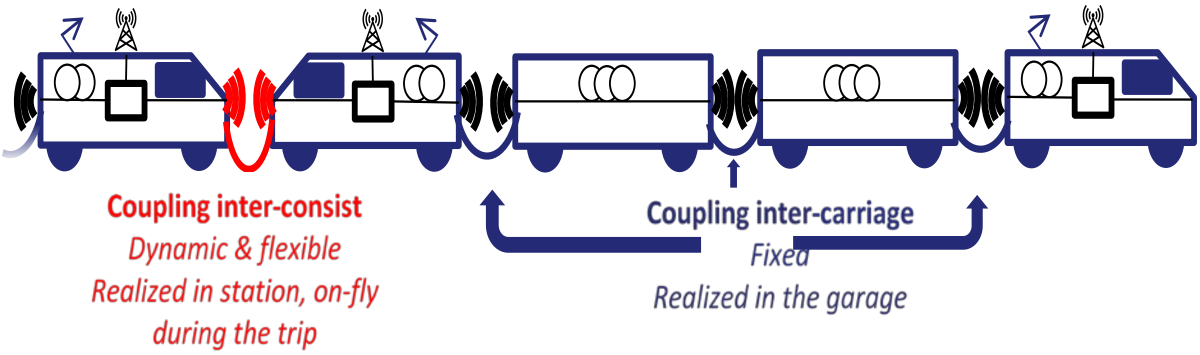

Figure 1. Wireless onboard telecommunication network

Train Control and Monitoring System (TCMS) is an essential train subsystem for the functional onboard integration with other subsystems such as brakes, lights, doors, etc. Whereas On-board Multimedia and Telematics (OMTS) conveys users and operator information. In order that all those subsystems can communicate with each other a Train Communication Network (TCN) is used. The standard (IEC 61375) defines the general TCN architecture in a hierarchical structure with two levels of networks, namely the Train Backbone Network (TBN) and the Consist Network (CN). TBN is responsible for the communications between the consists or what is referred to as inter-consist communications, whereas the CN establishes the communications in or among carriages that cannot be split apart during operation or what referred to as intra-consist communication.

With the increasing demand in passenger and freight transportation, railway networks are approaching their capacity limit, especially in densely populated areas and on highly frequented lines. This leads to a lack of flexibility within the railway operation, resulting in delays and overcrowding for passengers or the lack of transportation capacities in the case of freight transportation. An expansion of the railway infrastructure is not always possible due to the lack of space for additional rails, platforms or stations. In addition, new infrastructure is very cost-intensive, while the planning, permission and building takes a long time. Furthermore, the telecommunication infrastructure deployed in trains is currently very simple and based on a wired system that requires cables set up and a physical coupling between the trains. Due to the cables cost and the difficulty of the maintenance and diagnosis, the efficiency of this onboard network could be greatly improved using innovative technologies such as advanced wireless technologies and network virtualization.

Hence, a New Generation Train Communication Network (NG-TCN) has emerged as a major innovation of the European Railway industry introducing a wireless architecture as an enabler to enhanced automation, flexible train management and increased railway capacity. NG-TCN targets replacing parts or the whole railway vehicles wires with wireless technologies. NG-TCN involves Wireless Train Backbone (WLTB) and Wireless Train Consist Network (WLCN) for inter-consist and intra-consist communications respectively.

NG-TCN allows to remove the inherent cost of cabling and connectors of traditional wired train control networks. A reliable and performant NG-TCN is basic for the introduction of new functions such as the Train Integrity function which will help reducing trackside equipment, and therefore costs. NG-TCN aims to increase the system availability and capacity of the train backbone by removing the connectors in the coupler to bring more flexibility and scalability than the existing wired solutions. It also allows the adoption of train backbone in existing rolling stock where the installation of new cabling is difficult or even impossible. In addition, NG-TCN will enable innovative applications such as wireless virtual coupling and train platoons.

Virtual coupling [Ref **1**], is based on mutual information exchange between trains regarding velocity, position, braking characteristics. It allows trains to move at a closer distance than the traditional distance allowed by the conventional Absolute Braking Distance Supervision (ABDS) concept. In the virtual coupling concept, trains consider the velocity and braking curves of the front train, in addition, to those of itself. Thus, the distance between trains is further reduced. Virtual coupling aims to achieve multiple objectives such as to increase line capacity, increase operational flexibility, reduce infrastructure costs and enhance competitiveness versus road transportation.

However, many challenges lie ahead in the NG-TCN migration, such as uncontrolled interferences from the coexistence onboard and at the station wireless systems. In addition, wireless channels are unstable and are prone to many random effects from the surrounding environment. Furthermore, due to the random behavior of wireless signals, data rate, latency and other metrics are time variant. Moreover, wireless communications are more vulnerable to security threats such as jamming and eavesdropping. Hence, wireless solutions will need to be carefully selected and adapted to the peculiar rail environment [Ref **2**].

3.2. Train Domains

3.2.1. General Information

In this subsection we will present the services provided by the train domains in order to take that into consideration in the system design.

Train services can be classified in the following three function domains: Train Control and Management System (TCMS), Operator Oriented Services (OOS) and Customer Oriented Services (COS) as illustrated in Figure 2. Normally in the railway activities, those three domains can be grouped into two areas TCMS and On-board Multimedia and Telematics (OMTS), with OMTS that includes both OOS and COS domains.

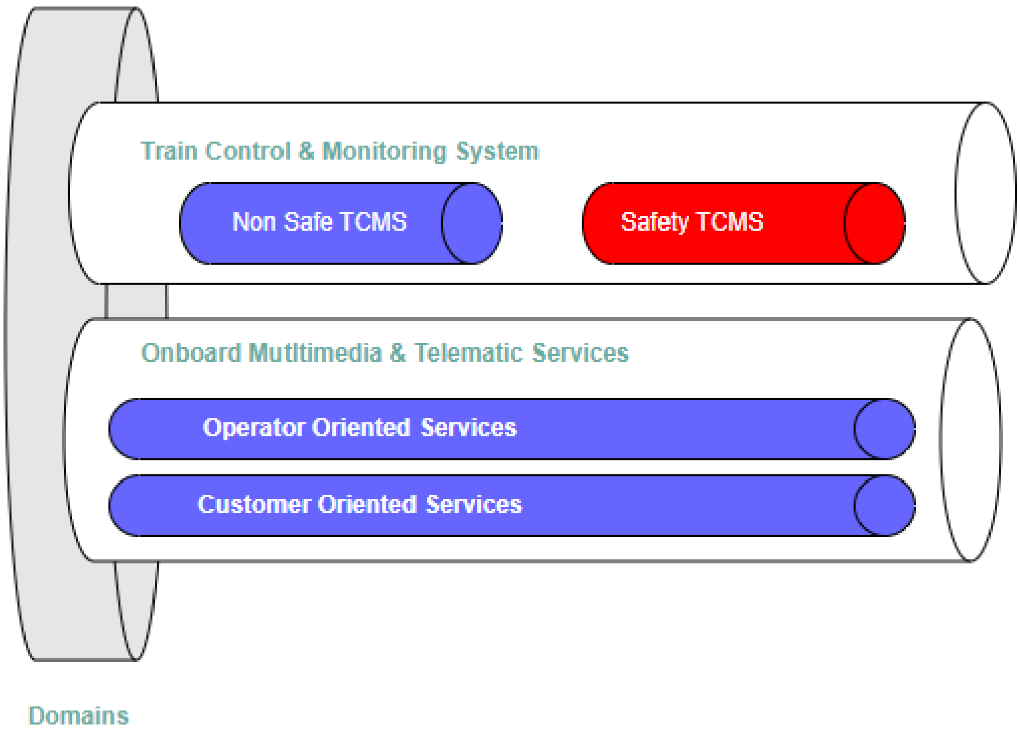

Figure 2. Train services domains

In the TCMS area, we found the following functionalities/systems:

- Main command
- Train radio
- Air conditioner
- Drive
- Brakes
- Electricity
- Bathroom
- Lighting
- Support systems
- Passenger announcement system
- Exterior & interior doors
- ETCS (European Train Control System)
- ATP (Automatic Train Protection)
- ODDRS (Onboard Driving Data Recording System)
- Passenger alarm system

The TCMS area can be divided into two subareas, safe TCMS and non-safe TCMS. The safe notion comes from the SIL (Safety Integrity Level) associated with each service. Generally, in the TCMS, there are 3 SIL granularities:

- SIL4
- SIL2
- SIL0

The highest degree of risk of is SIL4 (Risk Reduction > 10,000), whereas SIL0 (not existing in the SIL classification) indicates that European standards have not required an additional level of security, which is the case of non-safe TCMS. Please refer to the European standard IEC 61508 for more information about SIL classification.

In the OOS area, we found the following functionalities/systems:

- CCTV: protection video, in-cab track monitoring, rear vision.
- Infotainment onboard train devices.
- Automatic passenger counting.
- Vehicle positioning-service (also exists in TCMS domain).
- Fare management or ticketing.
- Driving assistance system.
- E-schedule (schedule for the driver).
- Diagnostic systems and CBM (condition-based maintenance) (service exists in the TCMS domain as well).
- Passenger Information System (PIS): Automatic Announcements.

The COS functions which will be considered will be those that processed via “gateway” type equipment. These gateways also manage the flows from the OOS domain. The COS functions/systems are as follows:

- User equipment access (example Wi-Fi hotspots).
- Public internet access.

In addition, the services can be conveyed by different communication sources:

- VCU (Vehicle Control Unit).
- Device: equipment installed or operating on board.

3.2.2. Train Domains Requirements

Table 1 provides the expected network performance identified by Roll2Rail project for the WLTB based on the current network uses, as well as the network performance expected by the NG-TCN. It is worth mentioning that the minimum requirements to be fulfilled are the ones which match the current use. However, the requirements integrated by the NG-TCN are also considered in order to keep the functional compatibility of WLTB with the NG-TCN. Roll2Rail project defines the requirements needed by both TCMS and OMTS domains in term of data rate, latency and jitter.
From Table 1, it can be deduced that the radio technology to be adopted for the TCMS domain must provide a data rate of 43 Mbps (30 Mbps 70%) with minimum cycle times of 20ms, and minimum latencies equal to 60ms. Regarding the current use OMTS domain, it has a minimum data rate requirements of 50 Mbps (35.2 Mbps 70%) with minimum latencies of 100ms.

For future integration of the WLTB in the NG-TCN the requirements in terms of data rate, TSN features, latency and jitter are much more demanding. From Table 1, it can be deduced that the radio technology to be adopted for the TCMS domain, fully compatible with NG-TCN, has an aggregated data rate requirement of 240 Mbps with maximum cycle times of 1ms, minimum latencies of 15.92ms and a maximum jitter equal to ± 1%. For the OMTS domain, a minimum data rate requirement of 269.2 Mbps with minimum latencies of 100ms.

However, the mentioned requirements values in addition to other requirements such as the maximum communication distance will be thoroughly investigated during the progress of the project in order to be well identified and validated.

SCOPE	DATA CLASS		DATA SIZE (octets)	DATA RATE NEED		CYCLE TIME		LATENCY [1]		JITTER	
				Current Use [2]	NG-TCN	Current Use [2]	NG-TCN	Current Use [2]	NG-TCN	Current Use [2]	NG-TCN
TCMS	Process Data	time sensitive	≤ 1432 [acc. IEC61375-2-3]	N/A	≤ 100Mbit/s	N/A	≥ 1 ms	N/A	$T_L = \sum T_{Sn}$ (Example: n=128 → T_L = 15.92ms)	N/A	± 1%
		normal	≤ 1432 [acc. IEC61375-2-3]	10Mbit/s	≤ 100Mbit/s	20ms	≥ 10 ms	Between 3CycleTime and 7CycleTime	$T_L = 2 * \sum T_{Sn}$	N/A	± 50%
	Message Data		≤ 65388 [acc. IEC61375-2-3]	10Mbit/s	≤ 10Mbit/s	N/A	N/A	250ms	≤ 500 ms	N/A	Not relevant
	Supervisory Data		Not relevant	10 Mbit/s	≤ 10Mbit/s	Not relevant	50ms	250ms	$T_L = 2 * \sum T_{Sn}$	N/A	Like process data (normal)
OMTS	Streaming Data	Audio	N/A	≤ 3.2 Mbit/s (100 Kbit/s audio channel, one per consist)		N/A	N/A	≤ 100 ms		N/A	For synchronized A/V Stream: ≤ 80ms difference (lipsynch); minimal jitter
		Video	N/A	≤ 32 Mbit/s 1 Mbit/s video stream [no needs for HD]	≤ 256 Mbit/s (one stream rear-/side-/internal view per consist 8Mbit/s video stream [HD])	N/A	N/A	≤ 500 ms	≤ 100 ms		
	BestEffort Data		≤ 4 GB	Not relevant	≥ 10Mbit/s	N/A	N/A	Not relevant		Not relevant	Not relevant

Table 1. Train Domains requirements (Roll2Rail Project)

4. Work Methodology

4.1. Methodology Steps

In order to achieve the objectives of the project, the following steps will be adopted:

- Define the user needs of the wireless TCMS system in order to identify the system requirements at both inter and intra-consist levels for all TCMS domains.
- Investigate the different possible scenarios of the new system implementation in order to set up the specifications for consist and backbone network.
- Perform state of the art to survey the candidate wireless technologies that could answer the system requirements such as LTE-V2X, UWB, ITS-G5 and NR-V2X. In addition to the technologies, a literature review of the different channel models for such a system in railway environment types needs to be conducted.
- Analyze the coexistence of the system with other wireless technologies in the vicinity of the train such as the onboard passengers Wi-Fi, Wi-Fi at the stations other systems such as GSM-R, and Future Railway Mobile Communication System (FRMCS).
- Perform performance analysis of the candidate wireless technologies based on in-Lab evaluation experimentation and simulations in Matlab. The different technologies will be compared in terms of the metrics of interest such as data rate, latency and propagation characteristics.
- Propose a possible robust, safe, and versatile system architecture, that meets the system requirements and compatible with the railway constraints.

4.2. Key Performance Indicator (KPI)

NR-TCSM involves various domains (safe TCMS, non-safe TCMS, OMTS) with different requirements. Hence, it is important to define the system metrics and KPIs in order to analyze the performance of the candidate technologies and compare them in function of those KPIs.
Among the wireless communication system performance metrics, we can mention the following KPIs that are relevant to our case of interest:

- Data Bit Rate (the number of bits that are conveyed or processed per unit of time).
- End to end latency (the time taken for a packet to be transmitted across a network from source to destination).
- Maximum and minimum coupling time (the required time to carry out the coupling process).
- Communication Range (maximum coupling distance).
- Interference resilient (immunity against interference signals).
- Security (protecting information from unauthorized access, use, disclosure, disruption, modification, or destruction to provide integrity, confidentiality, and availability).
- Bit Error Rate (BER) (ratio of quantity of bits received in error by the total number of bits transmitted within the same time period).

- Packet Error Rate (PER) (ratio of quantity of packets received in error by the total number of packets transmitted within the same time period).
- Jitter (the interval between two times of maximum effect (or minimum effect) of a signal characteristic that varies regularly with time).
- Medium access (Deterministic/non-deterministic).
- Maximum number of nodes per network.
- Retransmission time (time interval to consider that the transmission has failed).

5. Requirements and User Needs

5.1. Overview

This section discusses the project requirements and their impact on the design of the new radio train communication network (NG-TCN). The requirements that are mainly taken are the different train types, various environments, coupling modes, Interference resilience, and security as illustrated in Figure 3.

Following the publication sub-147, very precise temporal alignment or time sensitive function (TSN) is excluded. Hence the technologies relying on TSN will not be considered.

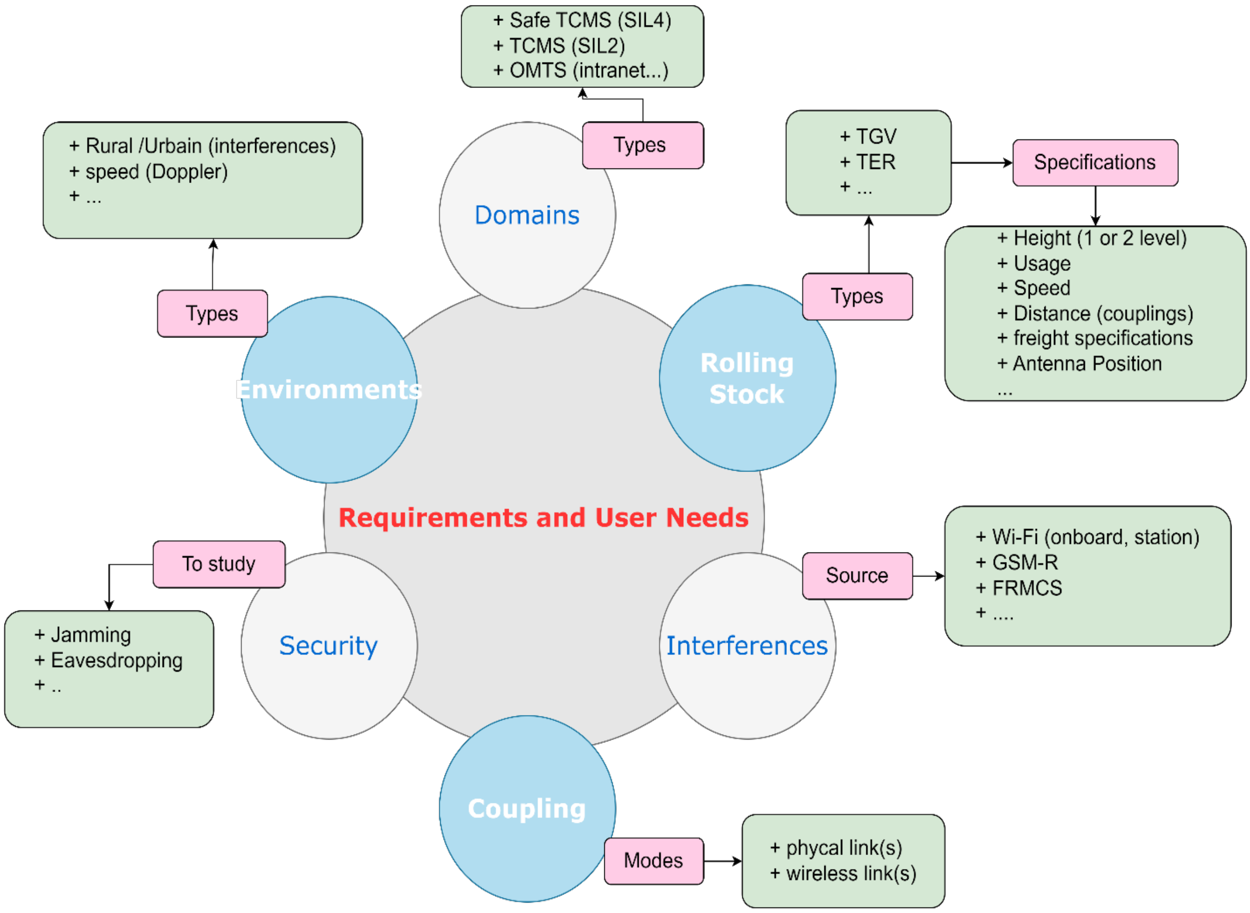

Figure 3. User needs and requirements

5.2. Different Trains Type

The wireless system must take into consideration the different types of train such as:

- High Speed trains
- Train with Significant passengers
- Regional Trains
- Rail Freight Trains
- Metro

Considering the variety of trains, it has been decided for this project to focus on the following train families:

- TGV Duplex or Euroduplex
- TER 2N NG

	TGV Duplex or Euroduplex	Z 24500 / Z 26500 TER 2N NG
Configuration	M + 8 R + M	From 3 to 5 cars
Length	200.19 m	2c: 54,70 m 3c: 81,10 m 4c: 107,50 m 5c: 133,90 m
Width	< 2,9 m	< 2,9 m
Height	< 4,320 m	< 4,320 m
max speed	< 320 km/h	< 160 km/h

Table 2. Technical specifications of trains of interest

The different types of trains impose different breaking distances, and hence the proposed wireless system should consider a technology that secures the inter-consist connection for the largest breaking distance. Additionally, due to the fact that trains roll at different speeds, the proposed wireless system should consider the effect of the speed on its functionality especially in terms of channel model and doppler effect. Furthermore, the physical antenna requirements such as place, height and orientation should be taken into consideration for all different train families for both outside (inter-consist) and inside (intra-consist) scenarios.

5.3. Different Environments

The proposed wireless communication system should take into consideration the different environments that the train circulates in such as urban, semi urban, rural and dense areas. This requirement imposes on the system to take into account the radio channel models that correspond to all environment types. Furthermore, the channel model should cover train-to-ground as well as Train-to-train scenarios.

5.4. Train Domains

As discussed in section 1-2, in the train there are three different types of domains namely safe-TCMS, non-safe TCMS and OMTS. According to its functionality, each of these domains has different requirements in terms of data rate and latency refer to Table 1 and Table 2. Hence, the new proposed wireless system should be capable of providing adequate resources to each domain to meet the requirements imposed by each domain. The new system should support the aspects of ultra-reliable low-latency communication (URLLC), Enhanced Broadband (EBB) and Massive Machine Type Communication (MMTC). Furthermore, due to the different nature of the TCMS domains, it is preferable that the new system can leverage high layer virtualization techniques to provide virtual infrastructure to each service to meet its specific requirements.

5.5. Coupling Functionalities

Two types of coupling are considered in this project namely mechanical and virtual coupling. In the conventional coupling mode and for safety reasons, it is recommended to keep safety TCMS services on wired based communication, while transmitting the other domains wirelessly. As a result, the new generation system should be capable of considering all coupling modes (virtual and mechanical). In addition, the proposed system should consider the data overhead resulting from the virtual coupling from transmitting additional information such as braking curve, speed and positions of the consists. Furthermore, the system should guarantee that only the involved trains are coupled and avoid coupling unwanted trains in virtual coupling operation.

5.6. Interference Resilience

One of the major challenges to the NG-TCN is the interference of the coexistence wireless systems in the railway environment such as the FRMCS, GSM-R and the Wi-Fi. Therefore, the proposed system should adopt interference mitigation techniques or consider new frequency bands to operate on to avoid any potential interference with the existing/installed wireless systems.

5.7. Information Security

Due to the sensitivity nature of the TCMS commands, the NG-TCN system should apply physical layer security techniques to ensure the integrity of the data and protect it against all malicious attacks such as eavesdropping and jamming.

6. Scenarios and Use Cases

6.1. Introduction

In this section we will investigate the possible scenarios of functionalities based on the user cases and the coupling modes. As the two coupling modes mechanical and virtual are completely different in terms of how consists are connected, the proposed scenarios take those constraints into account. In addition, due to the sensitivity of the safety services, the proposed scenarios provide a secure wired-based communication to guarantee the safety of the passengers. Wherein, different communications infrastructures are used for safety-based functions and non-safety functions.

The train communication network consists of two sub networks namely intra-consist and inter-consist. **Intra-consist** network is composed of intra-carriage and inter-carriage networks**. Intra-carriage** consists of End Devices (ED) or/and Wireless End Devices (WED) that communicate with each other at carriage level using a switch or Wireless Access Point (WAP) respectively. It is worth mentioning that some end devices cannot be replaced with wireless ones for technical reasons. **The inter-carriage** network secures the communication among the carriages in wired manner by using a consist switch (CS) or what referred to as Ethernet Consist Network (ECN), or in wireless manner using WAP. **Inter-consist** network acts at train backbone level, it performs inter-consist communication either wirelessly using Wireless Train Backbone Nodes (WLTBN), or via Ethernet Train Backbone Nodes (ETBN).
The current TCN is based on Ethernet at both intra-consist and inter-consist levels, to carry out the communications among trains and carriages as illustrated in Figure 4.

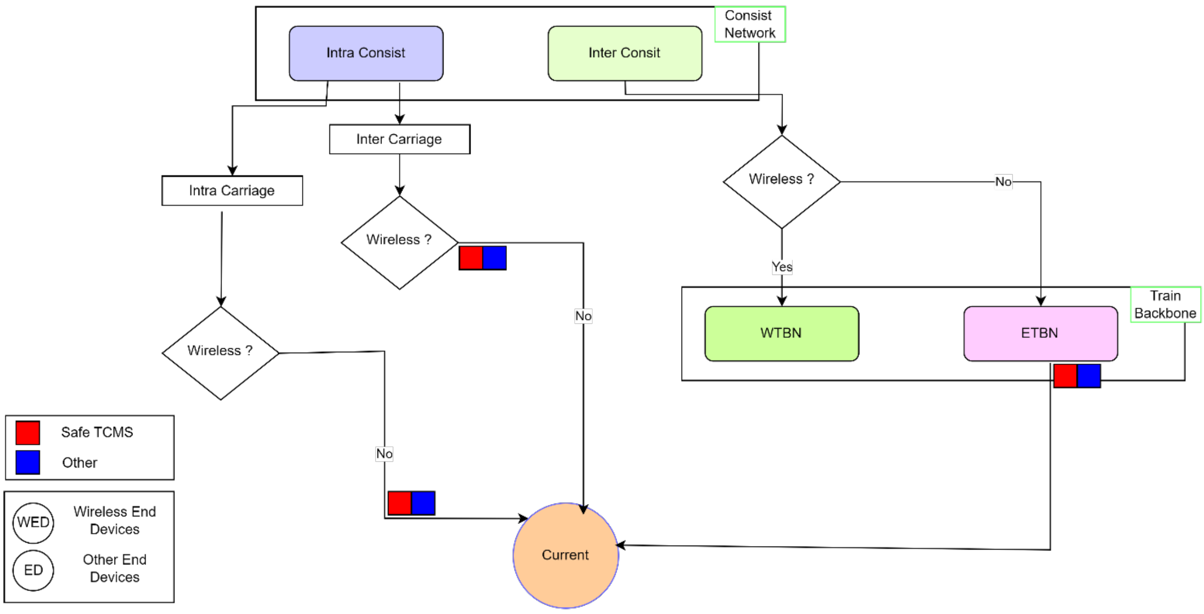

Figure 4. Current TCN usage case

6.2. Ethernet Intra Consist-Hybrid Inter Consist

In this approach we maintain the consist network based on the ethernet (ECN) at the intra-consist level for both safe and non-safe domains. At the inter-consist level and for safety reasons, safe TCMS is kept connected via the Ethernet Train Backbone (ETB), while a wireless train backbone (WLTB) is used to carry out the communication wirelessly for non-safe TCMS and OMTS. It is worth mentioning that this approach can work only in mechanical coupling mode.

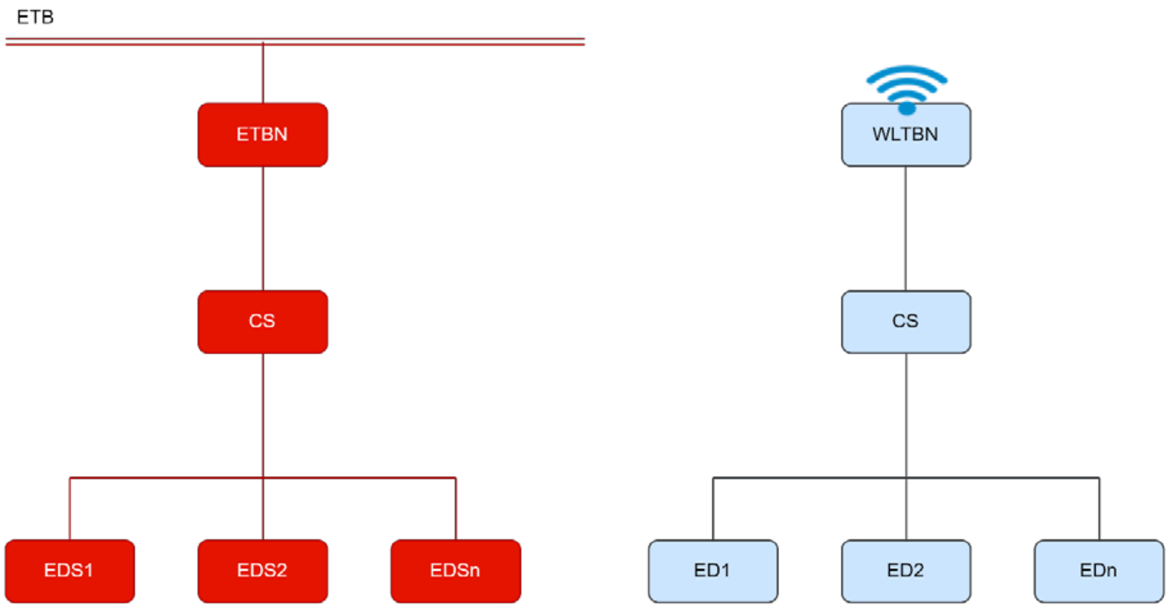

Figure 5. Scenario 1 NG-TCN architecture

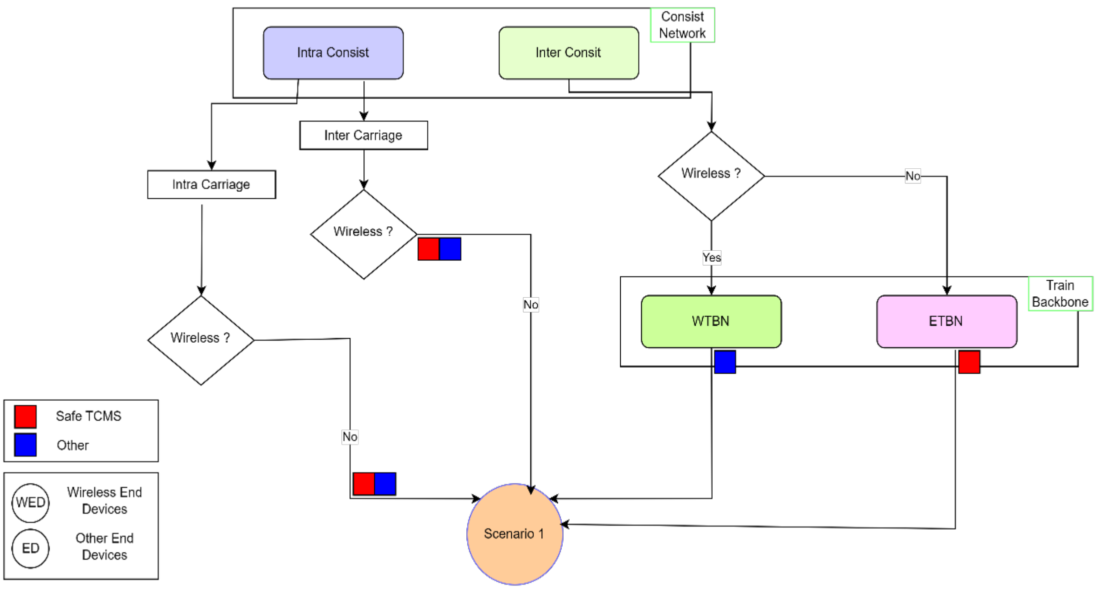

Figure 6. Scenario 1 usage case

6.3. Hybrid Intra Consist-Hybrid Inter Consist

Similarly, Scenario 2 maintains the safe-TCMS domain ethernet-based at both intra and inter-consist levels. Whereas wireless communication will be adopted for non-safe TCMS and OMTS domains at inter and intra consist communication using wireless access points (WAP) and wireless train backbone nodes (WLTBN) respectively. Wherein the end devices (ED) are replaced (when possible) with Wireless End Devices (WED), and those wireless end devices are connected to a WAP to carry out the intra-consist communication in a wireless manner. The end devices that cannot be replaced with wireless ones will be connected via a Consist Switch (CS) at the carriage level and the latest will convey the end devices flow to the corresponding WAP to perform the intra-consist communication.

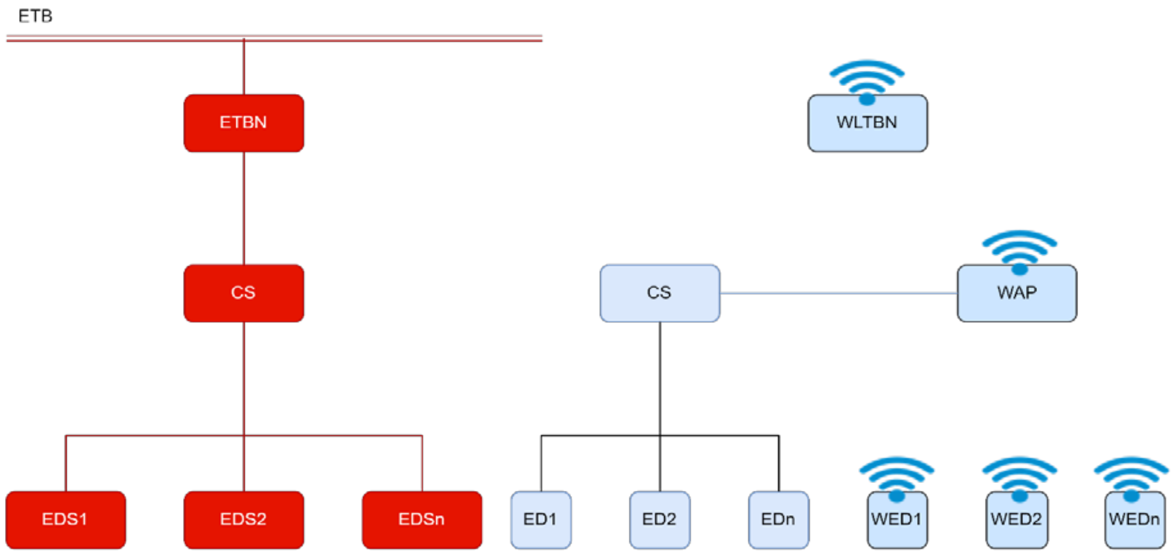

Figure 7. Scenario 2 NG-TCN architecture

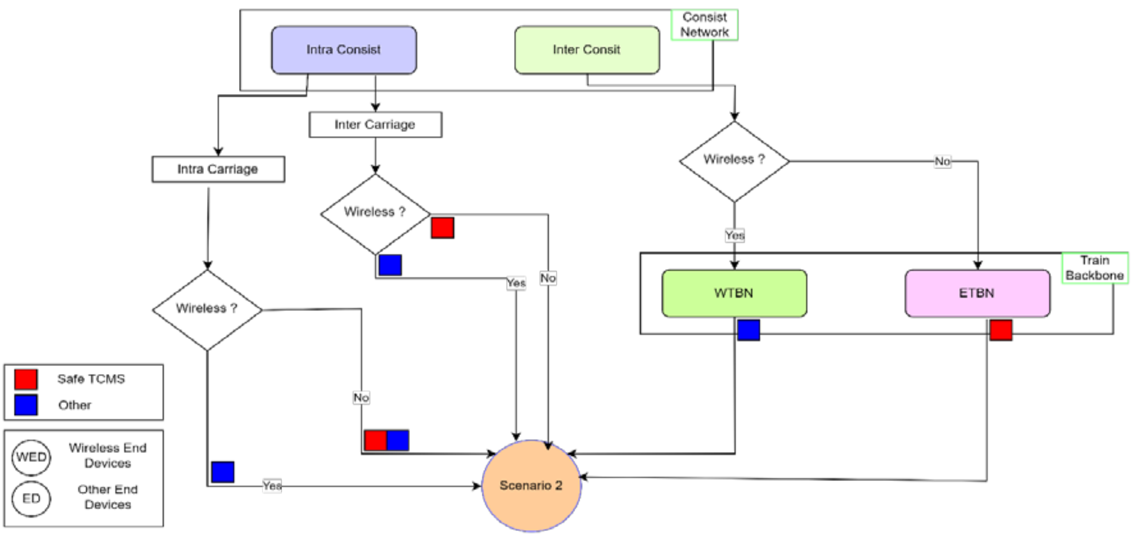

Figure 8. Scenario 2 usage case

6.4. Ethernet Intra Consist -Wireless Inter Consist

This approach maintains the structure of the ECN at the intra-consist level, but it uses wireless backbones for inter-consist communication for all domains (safe TCMS, non-safe TCSM and OMTS). It is worth mentioning that this approach can be applied in both mechanical and virtual coupling modes.

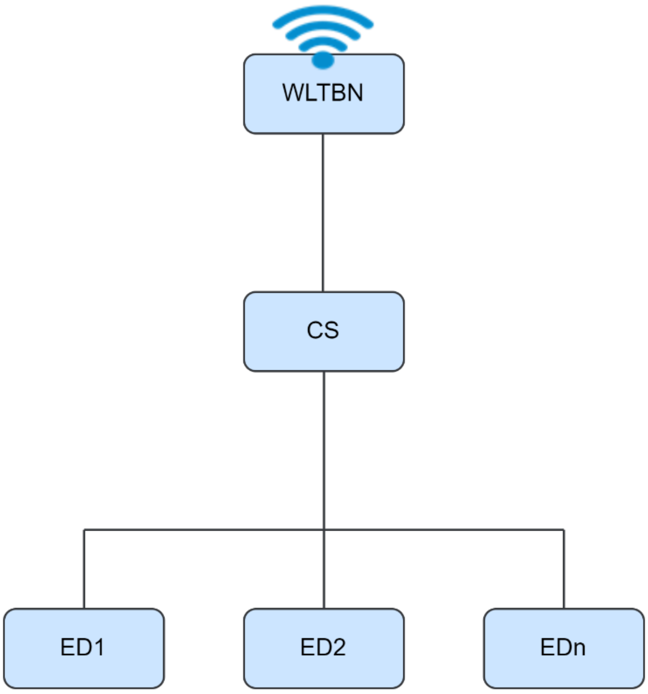

Figure 9. Scenario 3 NG-TCN architecture

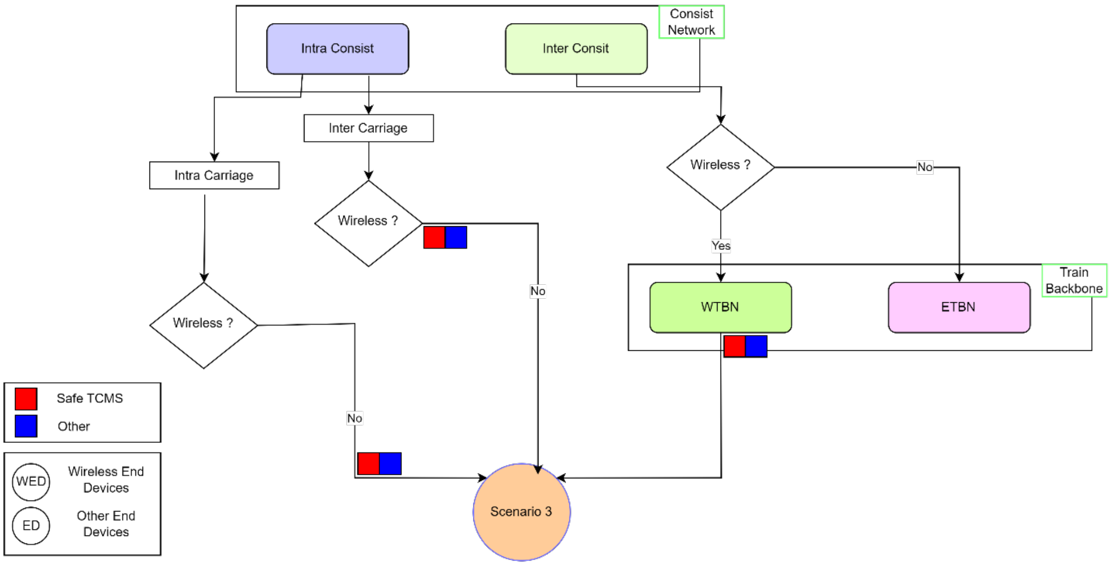

Figure 10. Scenario 3 usage case

6.5. Hybrid Intra Consist-Wireless Inter Consist

In this approach all end devices (that can be replaced), switches and wired backbone nodes are replaced by WED, WAP and WLTBN respectively for all domains at intra-consist and inter-consist levels. While keeping the end devices that cannot be replaced by wireless devices connected via switch, and the latest is connected to the WAP. This scenario can be applied in both modes of coupling mechanical and virtual.

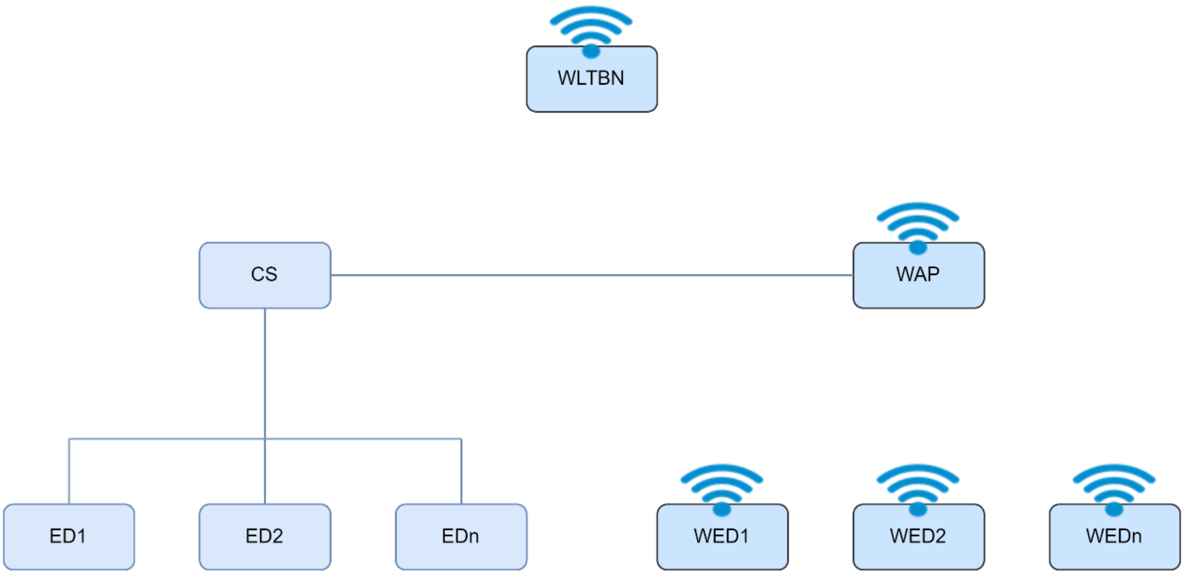

Figure 11. Scenario 4 NG-TCN architecture

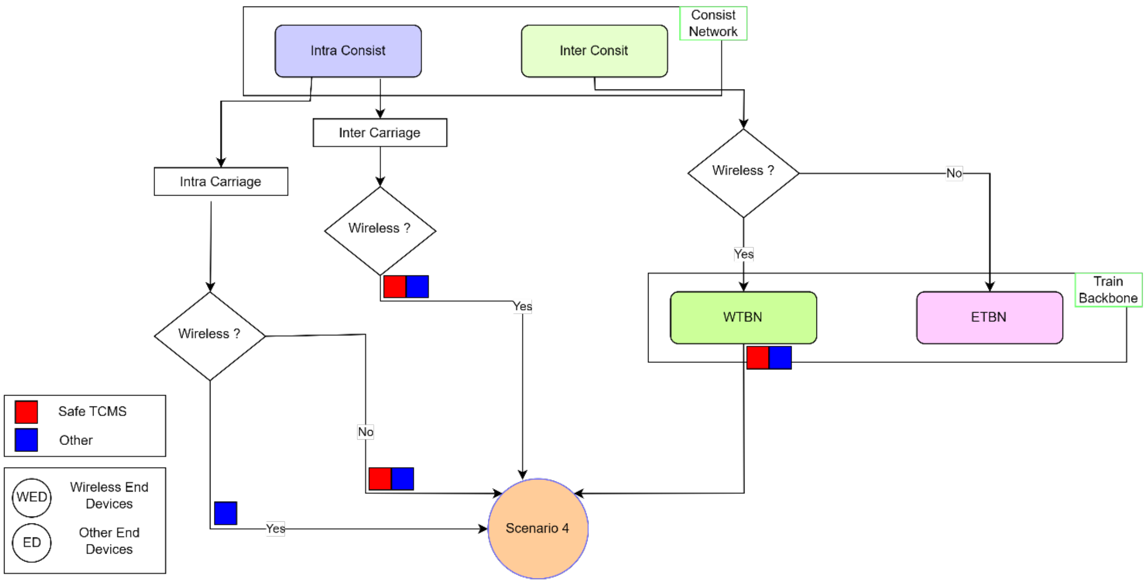

Figure 12. Scenario 4 usage case

7. State of The Art

7.1. NG-TCN Approaches

Many European projects have emerged to address the application of the NG-TCN in the future railway systems, among which we can cite Connecta-1-2-3 [Ref **3**], Safe4Rail-2 [Ref **4**] and Roll2Rail-2 [Ref **5**]. CONNECTA projects investigated the candidate wireless technologies that could meet TCMS and OMTS domains requirements for both Wireless Train Backbone (WLTB) and Wireless Consist Network (WLCN). CONNECTA concluded that none of the existing radio technologies satisfy completely the TCMS domain. On the contrary, the requirements of OMTS domain may be satisfied in theory by IEEE 802.11s Technology. CONNECTA refers to the New Radio V2X (NR-V2X) technology as the solution that seems to be the most appropriate technology to satisfy the WLTB requirements. Since the NR-V2X had not been standardized at the time, CONNECTA investigated the adoption of LTE-V2X with improved functionalities coming from LTE-D2D, that are expected to be a part of NR-V2X. As a conclusion, in order to cover all TCMS traffics in the WLCN, CONNECTA suggested a combination of the existing wireless technologies as the most valid approach.

Safe4Rail project proposed a demonstrator prototype for WLTB based on LTE-V2X with an additional overlay module to handle the missing features (service discovery, group communication and mesh networking). The project also investigated NR-V2X as a research activity as a potential wireless solution. Roll2Rail project investigated the technologies and the architectures to allow the development of NG-TCN based on wireless transmission with the goal to use them in TCMS, as well as other on-board systems. Roll2rail specifies the requirements of the NG-TCN system with particular focus on the communication systems at both WLCN and WLTB levels, including train to train communication.

The authors in [Ref **6**] investigated the applicability of the NR-V2X at WLTB communications. The results indicate that NR-V2X technology is suitable for WLTB, but in order to cover a large number of consists either high-end 5G configurations need to be used (such as 4x4 MIMO and beamforming in millimeter waves) or the requirements for the WLTB need to be scaled down. In [Ref **7**], an LTE-based WLTB system is tested in metro environments. Results illustrate that the system can transfer data at 3.2Mbps with acceptable Frame Error Rate (FER). The authors in [Ref **8**] investigated various available and future wireless technologies matching the requirements at both train backbone and consist levels. It was concluded that there is not a single wireless technology alone that is capable of matching all the NG-TCMS requirements. However, with the announced performance of the upcoming future NR-V2X, it is expected that this technology will play a major role for NG-TCMS. Two complementary strategies have been presented in [**Ref 9**], aiming to simulate and emulate TCMS traffic exchanges through LTE for a zero on-site testing approach. The strategies represent flexible solutions for realistic simulation and emulation of a wireless railway environment to evaluate the performance of Train to Ground exchanges of TCMS traffic in the laboratory, with the most realistic representation.

There exist some commercial solutions which remove the physical connectors by substituting them with wireless short distance links between cabins. They keep the cabling along the consist of the ETB. There is also the IEC TR 61375-2-7:2014 standard, that mainly focus on freight trains with distributed power. It does not include a fully automatic inauguration procedure. It must be assisted by the driver to provide the position of the locomotive in the composition.

7.2. Channel Models for NG-TCN

Channel model is an essential challenge for railway communications in general and for NG-TCN in particular. As due to train high speed velocity, peculiar channel models need to be investigated. However, according to our knowledge only a few works have investigated channel models for NG-TCN or Railways in general. A survey of channel models for high-speed trains is presented in [Ref **10**], [Ref **11**] and [Ref **12**]. In [Ref **13**] a stochastic channel model for the ITS-G5 frequency band is proposed for railway environment. Wherein measurements were performed in various railway environments for high-speed trains. The authors in [Ref **14**], present a measurement based on Tap Delay Line (TDL) channel model in the 5.2 GHz frequency band. Six tapped delay line channel models were provided for Train to Train (T2T) communications that cover different T2T distances and two railway scenarios for main lines environments: Hilly Terrain and Railway Station. TDL models for LTE evaluation in railway environments at 900 MHz band are proposed in ETSI 145 005 V13.3.0 [Ref **15**].

Even fewer works in the literature have addressed channel modeling for NG-TCN system, those works will be listed in this section. An intra-consist channel model for NG-TCN at 2.6 GHz is presented in [Ref **16**]. The authors presented a full characterization of the communications channel inside a train vehicle, for both narrow and wideband configurations for both a modern, continuous train, with no physical separation between cars, and a legacy, non-continuous train, with metallic doors separating cars. In [Ref **17**], the radio channel of the train backbone with the impact on adjacent trains (due to interferences) was characterized in three different scenarios: tunnels (arched and circular), open air and stations (pit-like and tunnel-like ones). The impact of this backbone link on both the adjacent train and the intra-consist scenario has been addressed as well. The results show that the train backbone link is far from being an ideal one, with many multipath components, but, on the other hand, very stable in all the considered scenarios. In [Ref **18**] channel measurements for the 2.6 GHz band in railway environments are presented. The measurements have been carried out in the subway of Madrid in different environments (tunnel, station and open-air scenarios). Wideband and narrowband measurements have been carried out, and Power Delay Profile (PDF), delay spread and pathloss exponents have been calculated. The results show a similar delay spread for all environments, indicating that the main influence for wireless links comes from reflections on the metallic structures inside the train, although some multipath is also coming from the surrounding environment. In [Ref **19**] the antenna propagation model has been characterized for a 5G WLTB. A ray tracing simulation has been performed with antennas installed on the roof of the train in order to obtain the most optimal antenna locations. Obtained results can identify potential locations for the antennas of the WLTB.

8. Candidate Wireless Technologies

8.1. Introduction

This section investigates the potential wireless technology (technologies) that might meet the requirements of NG-TCN in terms of data rate, latency, interference immunity and network dimension. In addition to other metrics that can be taken into consideration such as: mesh capabilities, group communication, frequency reuse capability and protection against electromagnetic inductions.

8.2. LTE-V2X

LTE-Advanced (LTE Release 10 and beyond) allows obtaining wider transmission bandwidths (up to 100 MHz) and higher data rates compared to previous generation by exploiting carrier aggression approach. In LTE users are grouped in categories, wherein each category can achieve a corresponding data rate depending on the channel quality of the category. LTE data rate varies from 10 to 600 Mbps for the downlink and from 5 to 102 Mbps for the uplink in LTE Release 14.
LTE-V2X is an LTE based technology that permits user devices to communicate between each other in vehicular scenario without eNodeB intervention using the Side Link (SL) concept introduced by LTE Proximity Services (ProSe) in 3GPP Release 12. LTE Release 14 defined two operation modes namely mode 3 and mode 4. In mode 3, the eNodeB performs the radio resource scheduling, whereas in mode 4 (ad-hoc mode), scheduling is carried out by users using listen-before-talk and semi-persistent scheduling to access the resources. The maximum data rate of the LTE-V2X technology is 27 Mbps in mode 4. The end-to-end latency in LTE-V2X is mainly determined by the scheduling process that includes the process of Window Sensing and Selecting. Window sensing process stores the activities of sensing the carries for the last 1000 subframes. Whereas, Window Selecting identifies the free resources to be used during the transmission and it requires between 20 to 100ms. Hence the estimated latency of the LTE-V2X is estimated between 20 to 100ms.
Regarding interference resilience, LTE-V2X implements Self-Optimization Network (SON) technique defined in LTE-Advanced Release 10 and beyond. This technique enables the nodes in the network to automatically configure and heal themselves. SON has interference related functions such as Mobility Load Balance (MBL), that deals with congestion and coverage optimization in the network, and Mobility Robustness Optimization (MRO), that deals with automatic error detection and correction.
As for the network dimension, LTE supports up to 200 users/nodes per network with maximum communication distance of 387,80m. This communication distance has been calculated using typical transmitter power and receiver sensitivity values and applying the intra-consist path loss model [Ref **4**].
LTE-V2X technology allows up to 27Mbps data rate and 50-100ms latency, therefore it does not fulfil the requirements for the TCMS domains, neither for OMTS domain. By contrary, it fulfils the transmission range requirements and the possibility of working in mode 3 and mode 4 allows its use in busy scenarios, i.e., busy junctions, train stations or depots, with a radio scheduling provided by the LTE network and therefore having a collision-free deterministic performance.

8.3. Ultra-Wide Band

Ultra-Wide Band (UWB) technology uses low transmit power to transmit short duration pulses of the degree of 1ns in time domain, consequently the UWB signal occupies large bandwidth in the frequency domain. UWB provides a maximum data rate of 27.24Mbps, with non-deterministic medium access where no latency range has been identified in the literature. UWB is immune against multipath and fading as due to short duration of the signal, the reflected signal has very short time window to collide with the original signal. Furthermore, as the UWB spreads under the noise floor, the interferences with other coexistence wireless systems are reduced. On the other hand, UWB uses ALOHA as the medium access technique, where nodes transmit directly without sensing the carrier which results in a collision and a reduced data rate. Regarding network dimensions, the maximum distance for UWB communication is 100m. This communication distance has been calculated using typical transmitter power and receiver sensitivity values [Ref **4**]. From the discussion above the UWB does not respond to the requirements of both the TCMS and OMTS domains in term of data rate and latency.

8.4. Wi-Fi

Wi-Fi technology is based on the IEEE 802.11 standard, it has different versions namely: e.g., 802.11a, 802.11b, 802.11g, 802.11n, 802.11ac, or 802.11ax. The main difference among the different versions generally lies in the physical and the medium access layer. Depending on the physical layer implementation, the theoretical data rate of the Wi-Fi versions varies between 2 Mbps to 4.8 Gbps Table 2. illustrates the maximum data rate of the different Wi-Fi versions. Device-to-device (D2D) communication is provided in 802.11s which modifies the Medium Access Control (MAC) layer in order to allow the devices to sense and access the carrier.

Protocol	Frequency (GHz)	Channel Width (MHz)	MIMO	Maximum Data Rate (Theoretical)
802.11ax (Wi-Fi 6)	2.4 or 5	20, 40, 80, 160	MU-MIMO	4.8 Gbps[4]
				2.4 Gbps[1]
802.11ac wave2	5	20, 40, 80, 160	MU-MIMO	1.73 Gbps[2]
802.11ac wave1	5	20, 40, 80	SU-MIMO	866.7 Mbps[2]
802.11n	2.4 or 5	20, 40	SU-MIMO	450 Mbps[3]
802.11g	2.4	20	N/A	54 Mbps
802.11a	5	20	N/A	54 Mbps
802.11b	2.4	20	N/A	11 Mbps
Legacy 802.11	2.4	20	N/A	2 Mbps

Figure 13. Wi-Fi versions specifications

Regarding latency, IEEE 802.11 implements Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) as medium access technique. CSMA/CS is non-deterministic technique, wherein latency cannot be predicted and therefore Wi-Fi does not support real time applications. However, the latency in Wi-Fi technology varies between 1 to 20ms. Regarding Interference immunity: Wi-Fi operates on the ISM unlicensed bands 2.4 and 5 GHz, hence it is prone to many interferences from other wireless signal operating on the same frequency. However, Dynamic Frequency Selection (DFS) technique was implemented in In IEEE 802.11h to avoid interferences. DFS scans the occupied channels in the 5 GHz ISM band and avoids using those channels. Wi-Fi network can support hundreds of nodes per network with maximum communication distance of 216,49 using typical transmitter power and receiver sensitivity values.
From the above discussion, Wi-Fi can meet the requirements of TCMS and OMTS domains in term of data rate, however, its non-deterministic access behavior makes Wi-Fi not suitable for the TCMS domain especially the safe domain.

8.5. ITS-G5

Intelligent Transport System G5 (ITS-G5) has been developed by ETSI as an equivalent to the American Dedicated Short-Range Communication (DSRC) technology. ITS-G5 implements LTE-V2X functionalities over Wi-Fi to enable device-to-device communications in transport domain. Wherein, ITS-G5 applies the LTE techniques at the physical layer, and the Wi-Fi MAC layer techniques to leverage the device-to-device communication. Similarly to LTE-V2X, ITS-G5 provides a maximum theoretical data rate of 27Mbps. Regarding time consideration, the latency of ITS_G5 varies from 1 to 20ms. However, unlike LTE-V2X, ITS-G5 does not provide any mode with radio scheduling that may allow deterministic behavior. The maximum communication distance of ITS-G5 is 300m with up to 200 nodes/user per network. ITS-G5 doesn't fulfil the requirements of both TCMS and OMTS domains in terms of data rate and latency.

8.6. Synchronous and Hybrid Architecture for Real-time Performance (SHARP)

SHARP was essentially developed to meet the Ultra-Reliable and Low Latency Communications (URLLC) requirement in the automation domain. SHARP inherits IEEE 802.11g physical layer implementation by using OFDM as modulation scheme in addition to Time Division Multiple Access (TDMA) at the multiple access layer. However, in order to avoid the non-deterministic nature of the IEEE 802.11g, SHARP exploits Time Sensitive Network (TSN) standard to render the resource access process deterministic. SHARP is able to provide a data rate up to 54Mbps which is the highest achievable data rate for IEEE 802 standards without using MIMO. Regarding time consideration, SHARP provides ultra-low latency with maximum value of 0.5ms. As for network dimensions, SHARP can support a maximum of 20 users per network with maximum communication distance of 216m. In summary, SHARP cannot meet OMTS domain data rate requirement, however its ultra-latency feature makes it strong candidate for safe TCMS.

8.7. NR-V2X

New Radio (NR-V2X) technology has been identified in LTE Release 15/16 as an evolution of LTE-V2X technology in order to profit of the 5G aspects of Ultra-Reliable Low-Latency Communication (URLLC), Enhanced Broadband (EBB) and Massive Machine Type Communication (MMTC). NR-V2X adopts OFDM-Cyclic Prefix (CP) as waveform for both Uplink and Downlink, whereas LTE only uses OFDM-CP for Downlink. Furthermore, NR implements different subcarrier spacing than LTE with different slot duration. 5G uses two Frequency Ranges (FR): FR1 from 450MHz up to 6GHz, and FR2 (or millimeter waves) from 24.5GHz up to 52.6GHz, with 200MHz and 400MHz bandwidth respectively. NR-V2X can achieve a maximum data rate of 620 Mbps in FR1 and up to 1Gbps in FR2. NR-V2X is expected to provide latencies between 1 to 20ms. Interference avoidance in 5G can be carried out via Beamforming technique especially in millimeter waves. Regarding network dimension, NR-V2X can support 200 users per network and variant coverage depending on the adopted frequency.

From the previous analysis it can be concluded that none of the existing radio technologies satisfy completely the TCMS domain. By contrary, the requirements of OMTS domain may be satisfied in theory by Wi-Fi technology. NR-V2X seems to be the most appropriate technology to satisfy the NG-TCN requirements.

9. Conclusions

We introduced in this deliverable a work methodology to tackle the NG-TCN implantation, wherein both system requirements and possible implementation scenarios were introduced. User needs concerning different types of rolling stocks, environments and interference sources were considered. Four possible NG-TCN implementation scenarios based on consist and train backbone networks types have been also presented. In addition to a state of the art of the previous European project approaches of NG-TCN emigration. Furthermore, a survey of the possible wireless solutions such as LTE-V2X, ITS-G5 and 5G-V2X has been presented with their corresponding performance metrics.

In the future work, we will perform a comprehensive comparative study of the candidate wireless technologies in order to identify the wireless solution/solutions that meets the NG-TCN requirements and adopt the best to the railway environment. The comparative study will involve numerical and in-lab simulations in addition to real environment measurements. The performance of the candidate technologies will be thoroughly investigated with considering the coexistence interference sources in the corresponding channel models. Furthermore, we will propose a versatile, adaptive and safe architecture of the future TCN telecommunication system.

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