Wireless Technologies for the Next-Generation Train Control and Monitoring System

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***Abstract*—The Next Generation Train Control and Monitoring System (NG-TCMS) represents 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. This paper surveys various available and future wireless technologies matching the requirements both at train backbone and consist levels. Illustrating the challenges for a single technology to match all requirements, this paper also highlights the benefits of the upcoming 5G technology for future NG-TCMS.**

Keywords—5G-V2X, LTE-V2X, Wireless Train Backbone, Wireless Consist Network, 5G, NG-TCMS.

I. Introduction

European railway industry is positioning in order to remain a key player in the transportation sector in the upcoming years. For this purpose, the Shift2Rail (S2R) Multi-Annual Action Plan (MAAP) [1] has identified several areas of opportunities that need to be tackled. One of them is the migration of the current wired Train Control and Monitoring System (TCMS) to a wireless architecture. TCMS operates in a two-level network architecture, made of a Train Backbone (TB), which connects different consists or group of vehicles, and Consist Networks (CNs) inside each consist. The Next-Generation TCMS (NG-TCMS) will apply wireless technologies at both backbone and consist levels, thus creating WireLess Train Backbone (WLTB) and WireLess Consist Network (WLCN) solutions, which will increase the flexibility, ease interoperability, and reduce the cost of the currently wired solution. For this purpose, Safe4RAIL-2 [2] and CONNECTA-2 projects [3] are working in cooperation to develop specific solutions and to validate their functionality in two railway demonstrators.

While a wireless option is a clear target for NG-TCMS, the type of wireless technology has not been indicated and various current and future options are on the table. Yet, the technology selection should match the NG-TCMS requirements with the wireless technology capabilities, and it is not clear that a single technology might fulfill all NG-TCMS requirements. Some papers have been proposed to test a specific technology for a selected sub-category of the NG-TCMS services and functionalities (e.g. [4]). Yet, a study introducing the global NG-TCMS requirements and matching with a technology-agnostic survey of various available wireless technologies is still missing.

In this paper, we describe the vision and functionalities of the NG-TCMS, putting into perspective the performance requirements of wireless links for the WLTB and WLCN with the performance of selected wireless technologies. Our contributions are threefold: (i) we introduce the future NG-TCMS, in particular the WLTB and WLCN, (ii) we provide a technology-agnostic comparison of selected technologies (LTE, WiFi, VLC, ZigBee, WirelessHART,..) matching their requirements, (iii) we discuss 5G innovations that could be critical to NG-TCMS.

The rest of this paper is organized as follows: Section II introduces Railways Networking and NG-TCMS. Section III compares selected wireless technologies for WLTB, while Section IV does the same for WLCN. In Section V, we introduce key 5G features for NG-TCMS, while we conclude the paper in Section VI.

TABLE I. Major Acronyms used in Paper

Acronym	Definition
NG	Next Generation
TCMS	Train Communication & Monitoring System
WLCN	Wireless Consist Network
CS	Consist Ethernet Switch
ECN	Ethernet Consist Network
ED	End Device
ED-S	Safety-critical ED
ETB	Ethernet Train Backbone
ETBN	Ethernet Train Backbone nodes
WLTB	Wireless Train Backbone
WLTBN	Wireless Train Backbone nodes
LTE	Long Term Evolution
NR	New Radio
V2X	Vehicle-to-Everything
D2D	Device-to-Device
BLE	Bluetooth Low Energy
VLC	Visible Light Communications
eMBB	Enhanced Mobile Broadband
URLL	Ultra-Reliable Low Latency

II. Railway Networking

In this section, we provide a brief introduction of Railway Networking concepts in order to better understand the innovative paradigms and challenges required by future wireless technologies.

A. TCMS

The Train Control and Monitoring System (TCMS) is a subsystem of railway vehicles which is required for the functional onboard integration. For integration of other subsystem (brakes, axillaries, doors, etc.) the Train Communication Network (TCN) is used. The general TCN architecture is standardized (IEC 61375) as part of TCMS. This architecture defines a hierarchical structure with two levels of networks, Train Backbone (TBN) and Consist Network (CN), as depicted on Figure 1.

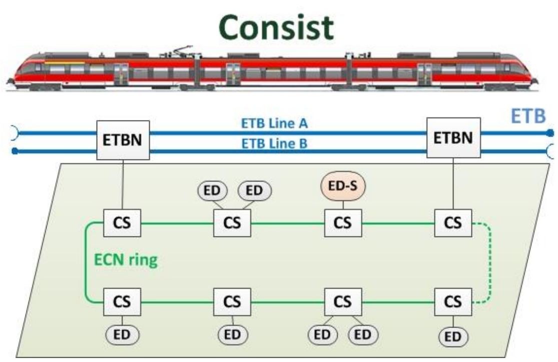

Figure 1 Example of a simple train communication network (TCN)

B. ETB

Two technologies are covered by IEC 61375 series for Train Backbone: the Wire Train Bus (WTB) and the Ethernet Train Backbone (ETB). The WTB provides deterministic data delivery by performing cyclically with a period of 25ms. It also allows sporadic data transmission for diagnostic uses. The content to be exchanged by WTB is specified by the UIC 556 standard. One of the main drawbacks found in WTB is its allowed data rate, which is limited to 1Mbps as it makes use of RS-485 in the physical layer. The ETB is based on Ethernet and overcomes the data rate limitation of WTB with a physical layer able to support up to 100Mbps. Equally to WTB, ETB allows dynamic train configuration in order to support train lengthening and shortening. The main shortcoming of ETB is that it is not deterministic, therefore not appropriate for time-sensitive functions.

A general problem which appears in both, WTB and ETB is the installation and maintenance cost of Train Backbone. The reason for that is twofold. On the one hand the train backbone needs a dedicated wiring along the train which increases the prices and becomes difficult to install in existing fleets. On the other hand, the connectors used between two trains when they are coupled, usually are source of failures due to the environmental conditions.

C. ECN

Consist Networks (CN) may be based on different technologies such as Multifunction Vehicle Bus (MVB), CANopen and Ethernet Consist Network (ECN) interfacing one Train Backbone. This paper is focusing on ECN technology only. The ECN is an IP based network, interconnecting systems on car and consist level. The ECN may use different topologies (ring or ladder structure) to achieve a robust and reliable communication network, distributing periodic and sporadic data. The network topology is built up by managed Consist Switches (CS). Other subsystems are connected to the switches to exchange information data within the consist and in the case of multiple consists also train wide (by making use of the ETB). A subsystem which is connected to the ECN is called end device (ED). IEC 61375-3-4 defines

- the data communication interface of EDs connected to the ECN,
- the functions and services provided by the ECN to EDs,
- the gateway functions for data transfer between Train Backbone and the ECN, and
- the performances of the ECN.

D. Wireless Railway Networking Challenges

One major innovation targeted for NG-TCMS is to replace parts of the railway vehicles wire by wireless technologies, with the objective to reduce cost, enhance maintenance and diagnosis as well as enable innovative applications such as wireless drive-by-wire or virtual coupling and train platoons. In this paper, we focus on two railway networking subsystems, the WLTB and the WLCN, where we expect most innovations from wireless technologies. Many challenges lie ahead, such as uncontrolled interferences, unreliable wireless links, unstable capacity and delay, not mentioning cyber-security. Wireless technologies will need to be carefully selected and adapted to the peculiar rail environment.

III. WLTB

The Wireless Train Backbone (WLTB) is an evolution of the IEC 61375-2-5 to provide a wireless alternative to the ETB. In particular, the major innovation in WLTB is to provide wireless communication between consists in order to avoid time losses due to manual coupling and improve the infrastructure capacity.

A. Architecture

The architecture proposed by CONNECTA-2 for the WLTB is depicted in Figure 2. This architecture is composed of one WLTB node (WLTBN) for each ECN plane, whose role is to provide single hop and multi-hop wireless communication between WLTBN of multiple consists of a same railway vehicle. WLTB may also be used to provide wireless communication between trains. Accordingly, WLTB must be capable of industrial wireless communications over short and long distance, and over single and multi-hop.

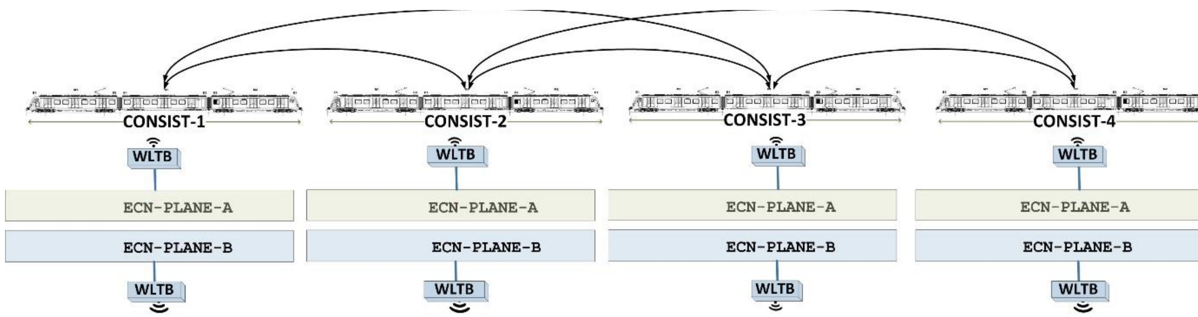

Figure 2 Proposed Mesh Topology Architecture for WLTB

The WLTBN will be connected to a Consist Switch (CS) for WLTB-ECN interconnection.

B. Requirements and potential technologies

Table I summarizes the key requirements defined by CONNECTA-2 for the WLTB, as well as the capabilities of selected wireless technologies for each of these requirements. Whereas all support Device-to-Device (D2D) communication, only ITS-G5/DSRC, WiFi (mesh) and BLE are capable of group communication and mesh networking. Critical for industrial wireless, BLE only provides a deterministic MAC, but has an incompatible delay and communication range. Both LTE V2X and ITS-G5/DSRC have been designed for low latency short-distance V2X communications, but only LTE V2X supports native frequency reuse between consists. With BLE, VLC is the only other technology providing native protection against interferences but would require a linear WLTB topology, which is not preferred by CONNECTA-2.

Accordingly, none of the selected current technologies matches the WLTB requirements. On the LTE side, railway networking requirements are scattered between the D2D and the V2X modes, and much lower latencies would be expected. Deterministic schedulers would be required for both LTE V2X and ITS-G5/DSRC technologies. With Bluetooth 5.0, BLE is expected to improve in delay and range, but its limited capacity might qualify it only for selected critical WLTB links, considering its native deterministic scheduling. VLC would need to be investigated in a railway environment, in particular considering optical railway wireless channels or LED durability in harsh railway conditions, but could provide a solid redundant technology to Radio Frequency (RF) technologies, as it is one of the few wireless/optical technology providing native interference protections.

The future NR V2X (LTE rel. 16) is expected to be a highly valuable technology for WLTB, in particular the URLL, and native group-cast communications. As of LTE rel.16, mesh networking has however not been addressed, which would then need to be conducted at a higher layer (IP or geonet/WAVE) to fulfill this requirement.

IV. WLCN

The Wireless Consist Network (WLCN) covers the communications inside each consist and towards the train backbone. The main difference with the WLTB lies in the fact that the WLCN requires a higher number of nodes and has to operate in a more complex propagation environment (e.g. reflections on metallic structures and cabinets, influence of passengers, etc).

A. Architecture

The architecture proposed by CONNECTA-2 for the WLCN is depicted in Figure 3. It is based on the IEC 61375 standard and on topology solutions provided by CONNECTA and Roll2Rail projects. This architecture is made of two redundant wireless networks, each of them having one Wireless Access Point (WAP) per vehicle.

Wireless End Point (WEPs) will be connected to a WAP, except the Safe Wireless End Points (WEP-S), which will be connected to two WAPs (which is a safety related design approach), each one from a different wireless network, and therefore will require two wireless interfaces. On the other hand, all WAPs will be connected to Consist Switches (CS), which will be interconnected via a wired Ethernet Consist Network (ECN).

This is a suitable solution for the NG-TCN, because it eases the integration of different wireless technologies. In the future, architectures with a complete wireless CN could be achieved; this would require deterministic and reliable communication for both non-safe and safe end devices.

B. Requirements and potential technologies

Table II summarizes the key requirements defined by CONNECTA-2 for the WLCN, and the values of the potential wireless technologies for each of these requirements. These values indicate that LTE and Wi-Fi provide the bit rate required for the WLCN, but LTE has high latency and Wi-Fi has a non-deterministic medium access. This means that for LTE to be used in the WLCN, Ultra-Reliable and Low-Latency Communications (URLLC) provided by 5G should be explored [14]; regarding Wi-Fi, deterministic extensions of the MAC layer should be used, which are currently being developed by several research initiatives [15,16]. On the other hand, ZigBee would be unsuitable for the WLCN, due to its low bit rate and non-deterministic access. Regarding WirelessHART, ECHORING and WSAN/WISA, they provide deterministic access and low latency, but they are low bit rate solutions and therefore they could only be applicable for low

TABLE II. WIRELESS TECHNOLOGIES FOR WLTB

		WIRELESS TECHNOLOGIES				
REQUIREMENTS		***LTE-V2X [5,6]***	***ITS-G5 [4]***	***Wi-Fi [7,8, 9, 10]***	***VLC [11,12]***	***BLE [13]***
Max. Bit rate	100 Mbps per traffic type	27 Mbps	27 Mbps	(1) <2.4 Gbps (2) <6.5Gbps (mmWave)	LED dependent up (2Mbps-60Mbps)	up to 2Mbps
Max. Latency	16-500ms	50-100ms	1-20ms	(1) 1 - 20ms (2) 5-250ms	30-40ms	50ms-1000ms
Medium Access	Deterministic	Non-Deterministic	Non-Deterministic	Non-Deterministic	Non-Deterministic	Deterministic
Communication Range	up to 820m	300m-1000m	300m-1000m	(1) > 200m (2) < 2m	5m-20m	50m-200m
Group Communication	Multicast/Group	-	-	(2) DOT11y	-	Clustering
Mesh Capabilities	up to 32 nodes	-	Geonet/1609.3	DOT11s	-	inter-cluster
Freq. reuse	1 / car	2-3	-	ISM, mmWave	Directional	ISM
Protect. against interferences	-	-	-	(1) DSSS+Freq Hopping (2) BeamForming	Beam Forming	Freq. Hopping

Note 1: General assumptions for each technology (frequency band, environment (LOS/NLOS), evaluation methodology,..) are described in the cited papers.
Note 2: Performance of VLC technologies are assumed in a vehicular context and strongly depend on the receiver LED and modulation [11,12].
Note 3: The required WLTB communication range includes optional multi-hop forwarding.

bit rate TCMS traffic (e.g. for the most safety-critical applications). As a conclusion, in order to cover all TCMS traffics in the WLCN, a combination of the existing wireless technologies would be the most valid approach.

V. 5G AS ENABLER FOR NG-TCMS

The ITU defines 5G features in three aspects: URLL, eMBB, and mMTC. Each of them is expected to be beneficial to NG-TCMS, URLL supporting mission critical control, mMTC integrating massive amount of railway vehicles sensors, and eMBB providing future multimedia services to passengers. The future NR V2X [2] (LTE rel.16) has been designed to support these features in a highly mobile vehicular environment and accordingly is expected to be a key enabler for future TCMS, in particular the WLCN and WLTB. Considering that the LTE rel. 16 has only been recently frozen, a couple of years will be required before NR V2X devices will be available. Yet, the LTE V2X (LTE rel.14) devices will yet soon be available. This section overviews the challenges of the LTE V2X for matching NG-TCMS requirements and highlights of NR V2X features to match them.

A. From LTE V2X to NR V2X

The LTE V2X (rel.14) is an extension tailored to automotive services of the LTE Proximity Service (ProSe) mode for Device-to-Device (D2D) already introduced in LTE (rel.12). Technically, ProSe has four modes: two supervised by an eNB (mode 1 and 3) and two ad-hoc (mode 2 and 4). LTE V2X relies on modes 3 and 4. Table III depicts the main differences between the D2D and V2X modes (mode 1/2 and mode 3/4). Considering that V2X has only one service and should communicate with all cars, service management and group communications are not available to LTE V2X. In the other hand, broadcast communication for D2D is only allowed for Public Safety. Finally, access to the ITS spectrum is only allowed for the V2X modes. According to the table, we can observe that the NG-TCMS requirements (in particular for WLTB) span over the different modes and neither LTE V2X nor LTE D2D can meet all requirements individually. The upcoming NR V2X will therefore be required for NG-TCMS.

[2] This paper focuses on access stratum and will address other 5G innovations, such as MEC or Slicing, in subsequent work.

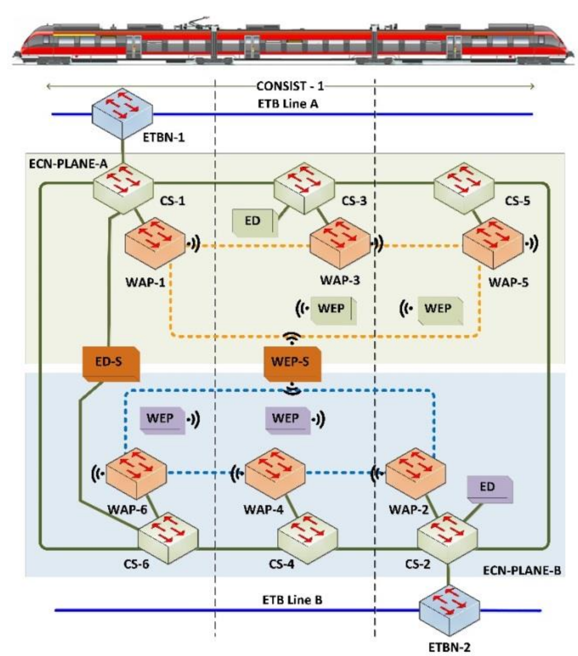

Figure 3 Proposed architecture for WLCN

TABLE III. WIRELESS TECHNOLOGIES FOR WLCN

REQUIREMENTS		WIRELESS TECHNOLOGIES					
		LTE [17,18]	***ZigBee [19]***	***WirelessHART [20]***	***Wi-Fi [7,8]***	***ECHORING [21]***	***WSAN/WISA [22]***
Max. Bit rate	~100 Mbps per traffic type	50 Mbps (UL) 150 Mbps (DL)	250 kbps	250 kbps	<1.73 Gbps	100kbps (9 nodes) 1Mbps (6 nodes) 5 Mbps (2 nodes)	4 x 1 Mbps (UL) 1 Mbps (DL)
Max. Latency	4 – 250 ms	50 – 300 ms	> 80 ms (25-50 nodes)	15 – 60s (50-100 nodes)	1 - 20 ms	<10ms(6–9 nodes) <200ms(11 nodes)	5 ms (typ.)
Medium Access	Deterministic	Deterministic	Non-Deterministic	Deterministic	Non-Deterministic	Deterministic	Deterministic
Communication Range	30 m (1 car)	400 m[a]	100 m[a]	100 m[a]	200 m[a]	30 m[b]	50 m[a]
Max. number of nodes	40 nodes / car	200 / cell	65000	Hundreds	Hundreds	<11	120
Protection against interferences	-	Dedicated band + MRO[c]	DSSS	DSSS + Freq. Hopping	IEEE 802.11h: DFS[d] (5 GHz)	Freq. Hopping + Coop. Automatic Repeat Request	Freq. Hopping + Freq. Div. Duplex (FDD)

a. Estimated from transmitter output power, receiver sensitivity, and intra-consist path loss model [23]
b. Measured value
c. Mobility Robustness Optimization
d. Dynamic Frequency Selection

Although the complete specification of the future 5G NR V2X is not fully defined at the time of writing, Table IV provides an overview of the key differences between LTE V2X and NR V2X [24]. Beside the highly anticipated increased capacity expected from any 5G device, a first major change relevant to NG-TCMS are the new NR V2X modes 1 and 2, which correspond to enhancements of the LTE V2X modes 3 and 4 with key features such as service discovery, group communication and new coordinated scheduling mechanisms. A second major innovation is the more flexible physical layer numerology, which enables a much lower latency and reactivity. Finally, NR V2X also unlocks potential deterministic schedulers with improved control planes (HARQ, NACKs, etc..), even in ad-hoc mode.

TABLE IV. KEY DIFFERENCES BETWEEN LTE D2D AND LTE V2X

Requirements	**LTE D2D**	**LTE V2X**
Service Discovery	Yes	No
Group Communication	Yes	No
Multicast/Broadcast	Mode 2	Broadcast
Spectrum access	Restricted	ITS
Mesh	higher layer	higher layer

B. 5G Key Features for NG-TCMS

1) Ultra-Reliable Low Latency Communications

NR V2X introduces several innovative features in order to support URLL. The support for mini-slot scheduling intervals will enable multiplexing multiple small packets requiring less than 1ms airtime, which would typically be required in WLCN. Moreover, the new NR-V2X mode 2 (ad-hoc) introduces 4 sub-modes for enhanced scheduling options [24]. Mode 2(b) and 2(d) for instance allows a UE either to assist or to assign resources for other UEs, thus enabling deterministic schedulers. Also, NR-V2X introduces a new 'short-term' sensing mechanism to better adapt to non-periodical traffic or to highly dynamic environments, which will be required to reach the NG-TCMS 4ms latency requirement.

TABLE V. KEY DIFFERENCES BETWEEN LTE-V2X AND NR-V2X [22]

Requirements	**LTE V2X**	**NR-V2X**
Service Discovery	No	Yes
Group Com.	No	Yes
Multicast/Broadcast	Broadcast	Multicast/Groupcast
Sub-carrier spacing	15kHz	15,30,60, 120kHz
Reliability	No	HARQ/NACK
Spectrum access	5.9GHz	6GHz & 60GHz*
Scheduling	Mode 3: eNB scheduling Mode 4: LBT, SPS	Mode 1: gNb scheduling Mode 2 : flex. sub-modes
Scheduling interval	sub-frame	minislot/multi-slot
Mesh	higher layer	higher layer

*NG V2X frequency bands are still under discussion at the time of writing.

2) Protection against Interferences

Protection against interferences will be one of the key requirements both to provide a reliable wireless link but also to protect against cyber-physical attacks. Although 5G spectrum is not fully frozen at the time of writing, the future NR V2X is expected to operate not only at 6GHz but also at the 30GHz & 60GHz bands. Directional beams in the millimeter wave range are not only expected to provide a massive increase in capacity, but also a solid directional link, which will strongly mitigate potential interferences and cyber-physical attacks.

VI. CONCLUSIONS

In this paper, we compared wireless technologies capabilities for the future NG-TCMS. We described the requirements for WLTB and WLCN and surveyed selected wireless technology for each of them. We notably emphasized that although some WLTB and WLCN requirements might be matched by some wireless technologies, not a single wireless technology alone is capable of matching all NG-TCMS requirements. By matching these requirements with the announced performance of the upcoming future NR V2X, we further illustrated that 5G is expected to play a major role for NG-TCMS in particular and in the Railway industry in general.

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