Applicability of 5G Technology for a Wireless Train Backbone

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***Abstract*— The migration of TCMS communications to a Wireless Train Backbone (WLTB) is one of the main goals of CONNECTA-2 and Safe4RAIL-2 projects of Shift2Rail initiative. In this paper the suitability of 5G technology for a WLTB is analyzed, both for infrastructure-based and V2X networks. Obtained results indicate that 5G technology is suitable for a WLTB, but in order to cover a large number of consists either high-end 5G configurations need to be used (e.g. 4x4 MIMO in millimeter waves) or the requirements for the WLTB need to be scaled down.**

***Index Terms*— 5G-V2X, LTE-V2X, 5G, Wireless Train Backbone, Railway.**

I. INTRODUCTION

Shift2Rail initiative of Horizon 2020 aims at providing novel capabilities for railway industry through research and innovation as defined in its Multi Annual Action Plan [1]. One of these capabilities is the use of wireless communications in the Train Control and Monitoring System (TCMS), which is one of the main goals of CONNECTA-2 and Safe4RAIL-2 projects. These projects are currently integrating several disruptive technologies for TCMS in two railway demonstrators, including deterministic communications, wireless communications, and virtual certification and validation environments.

The TCMS is a communication bus that operates in a two-level network architecture: a Train Backbone (TB), which connects different consists or group of vehicles, and Consist Networks (CNs), which are located inside each consist. The present work focuses on the Wireless Train Backbone (WLTB), and more specifically on the benefits that 5G technology can offer for its deployment. A preliminary analysis of wireless technologies for the WLTB was already done in [2], where the potential of 5G technology was pointed out. In the present work, a more detailed analysis is presented based on the different configurations and operational modes of 5G technology.

The rest of the paper is organized as follows: Section II introduces the approach currently followed by CONNECTA-2 and Safe4RAIL-2 projects, and Section III and IV present the possibilities of 5G technology for a WLTB in infrastructure and V2X configurations, respectively. Section V describes resource management enhancements for 5G-V2X, and a summary of the paper is presented in Section VI.

II. BEYOND-4G-V2X TECHNOLOGY FOR WLTB

From the requirements for the WLTB radio device detailed in [3] and [4], it was concluded that these requirements could not be fulfilled entirely by available 4G technology such as LTE ProSe Device-to-Device (D2D) or LTE-V2X. Accordingly, CONNECTA-2 and Safe4RAIL-2 have developed a Beyond-4G solution by following a hybrid approach: to rely on the LTE-V2X technology for the WLTB radio, and to add a management layer on top as an overlay (see Fig. 1). The LTE-V2X extensions consist of three key modifications from the Open Air Interface (OAI) ProSe Extensions:

1. *LTE-V2X Rel. 14 Physical Layer:* a different numerology and placement of Side-Link (SL) control and data planes.
2. *LTE-V2X LBT/SPS scheduler:* the LTE V2X rel. 14 default scheduler has been implemented as baseline, and alternative schedulers have been evaluated.
3. *LTE-V2X non-IP support:* LTE-V2X support to expose L2 interfaces and L2 addresses in order to manage L2 traffic described in IEC 61375-2-5 for Train Inauguration (railway-specific consist discovery protocol).

On the other hand, the overlay module developed on top of the OAI LTE-V2X software provides service discovery, group management and mesh management.

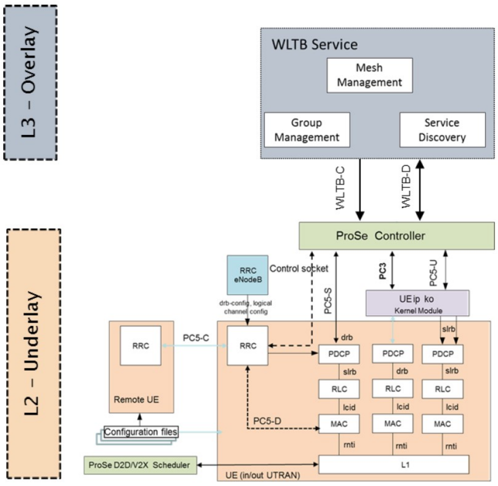

Fig. 1. WLTB radio device overlay/underlay architecture design [5]

III. INFRASTRUCTURE-BASED 5G FOR WLTB

In this section a numerical analysis is presented for a WLTB based on 5G technology with an infrastructure (i.e. with gNodeB).

A. *Network Topology and Traffic*

The infrastructure-based WLTB operates as a star topology, where the gNodeB acts as gateway managing the traffic which flows through the network (see Fig. 2). In this configuration, one User Equipment (UE) is deployed per consist, and one gNodeB per train.

The requirements for the traffic of the train backbone are detailed in TABLE I [6]. This traffic is split between periodic and aperiodic traffic, and it can be unicast or multicast. Therefore, a worst-case scenario in terms of capacity will occur when all periodic (PD, SD) and aperiodic (MD) messages are sent in the same subframe of 1 msec. This worst-case calculation is summarized in TABLE II, where 10 extra bytes have also been added to each traffic to account for the payload of the upper layers of 5G.

B. *Design of 5G-NR Resource Grid*

In order to determine if 5G-NR is able to cover the maximum traffic requirements detailed in TABLE II, a custom resource-grid has been designed.

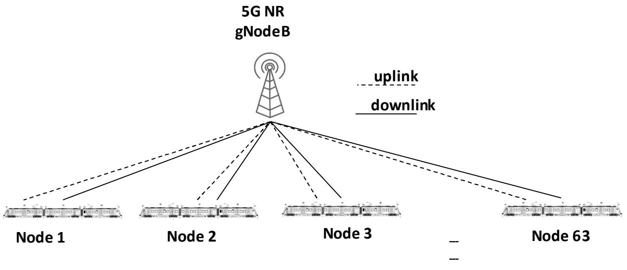

Fig. 2. Infrastructure-based 5G WLTB

TABLE I. TCMS TRAFFIC REQUIREMENTS [6]

	Process Data (PD)		**Message Data (MD)**	**Supervisory Data (SD)**
	Time Sensitive (TS)	***Normal (N)***		
Data Size (bytes)	1432	1432	65388	1500
Cycle time (ms)	1	10	N/A	50
Data Rate (Mbps)	100	100	10	10
Latency (ms)	4	8	250	8
	Periodic		***Aperiodic***	***Periodic***

TABLE II. TRAFFIC GENERATED PER NODE (BITS PER MILLISECOND)

PD		**MD**	**SD**	**TOTAL**
TS	***N***			
11536	1226	10080	320	**23162**

TABLE III. RESOURCE GRID: UPLINK (LEFT), DOWNLINK (RIGHT)

PRACH	
M (msg1-FSM)	8
SRS	
Symbols per slot	4
Density per RB (kTC)	4
RB$_S$	264
CSI-RS	
Density per RB	1
Slots density	4
PUSCH	
PT-RS RB density	2
PT-RS time density	1
DMRS time type	A
DMRS length	1
Additional DMRS symbols	0
DMRS freq type	2
DMRS freq density	4

SSB	
Aggregation Level	16
Coreset symbols	3
CSI- RS	
Density per RB	1
Slots density	4
PDSCH	
PT-RS RB density	2
PT-RS time density	1
DMRS time type	A
DMRS length	1
Additional DMRS symbols	0
DMRS freq type	2
DMRS freq density	4

PRACH: Physical Random Access Channel
SRS: Sounding Reference Signal
CSI-RS: Channel Status Information – Reference Signal
SSB: Synchronization Signal Block
CSI-RS in Downlink
PUSCH: Physical Uplink Shared Channel in Uplink
PDSCH: Physical Downlink Shared Channel
DM-RS: Demodulation Reference Signals
PT-RS: Phase Tracking Reference Signals
RB: Resource Block
SCS: Sub-Carrier Spacing

Due to the significant variability of the 5G parameters, several assumptions have been made for this design. For example, the most restrictive configuration has been adopted regarding the amount of resources occupied by reference channels and signals. The parameters involved in this configuration are specified in TABLE III. In order to obtain this restrictive scenario, it is assumed that the periodic information (PRACH, SRS, CSI-RS in Uplink, SSB and CSI-RS in Downlink) is transmitted in the same subframe as the data (PUSCH in Uplink, PDSCH in Downlink), and together with the reference signals DM-RS and PT-RS.

On the other hand, in 5G-NR two operating bands are available: Frequency Range 1 (FR1, below 7 GHz) and Frequency Range 2 (FR2 in millimeter waves, above 24 GHz). In FR1, the widest transmission bandwidth is 100 MHz with a full capacity of 273 RBs and a SCS of 30 kHz ($\mu=1$), while FR2 presents a maximum bandwidth of 400 MHz, a SCS of 120 kHz ($\mu=3$) and 264 RBs available ([7]). For this work it is assumed that the whole bandwidth is available, half for the uplink and half for the downlink transmissions (i.e. symmetric resource allocation). It is also considered that the streams from codeword codifications are directly mapped into RF ports and physical antennas, therefore allowing spatial multiplexing.

Based on the previous assumptions, full Resource Elements (RE) are obtained for both Uplink and Downlink: 91728 for FR1 (273 RBs x 2^1 x 14 symbols x 12 subcarriers) and 354816 for FR2 (264 RBs x 2^3 x 14 symbols x 12 subcarriers). Afterwards, REs which are reserved for channel control and signal references (see TABLE III) are subtracted from the initial planning obtaining the REs actually used for data transmission: PUSCH for Uplink and PDSCH for Downlink. Taking this into consideration, and depending on the configuration used regarding spatial multiplexing (i.e. number of antennas) and frequency range (FR1 or FR2), the maximum capacity offered by the 5G resource grid is obtained for different frequency ranges, antenna configurations and Modulation Coding Scheme (MCS) values (see TABLE IV). Four MCS values have been taken as representative between 0 and 28 (MCS=0, 10, 20 and 28).

C. *WLTB Traffic and 5G Resource-Grid Match*

Applying the WLTB traffic detailed in Section III.A to the resource-grid allocation described in Section III.B, required 5G bit rates have been obtained for different MCS configurations and for an increasing number of nodes, as shown in Fig. 3 and Fig. 4. These graphs indicate the required Uplink and Downlink 5G bit rates for different MCS values (only MCS 28 graphs are shown here for brevity). Up to 63 nodes have been considered, which is the maximum number of consists in a train.

Matching these graphs with the maximum capacity provided by each 5G configuration (see TABLE IV), the maximum number of nodes per configuration are obtained. These results are presented in Fig. 5 (Uplink) and Fig. 6 (Downlink) and show the maximum number of nodes that can be managed by a specific 5G configuration. From these results it can be concluded that a minimum configuration of 2 antennas in FR2 is needed in order to cover a full 63-consist train, while FR1 operation up to 22 consists is possible by using 4 antennas and MCS 28. However, it must be noted that this analysis has been made considering full bandwidth availability. This means that if the WLTB is to be operated with lower MCS values or lower number of antennas, the requirements for the WLTB should be scaled down.

TABLE IV. MAXIMUM CAPACITY (MEGABITS PER SECOND)

			MCS Index			
		Antennas	**0**	**10**	**20**	**28**
UP	**FR1**	**1**	6	33	83	138
		2	12	66	166	277
		3	18	99	248	415
		4	23	132	331	554
	FR2	**1**	36	205	512	856
		2	72	409	1024	1711
		3	108	614	1535	2567
		4	144	818	2047	3423
DOWN	**FR1**	**1**	9	49	112	205
		2	18	97	223	409
		3	27	146	335	614
		4	35	194	446	818
	FR2	**1**	38	207	474	869
		2	75	413	948	1738
		3	113	620	1422	2608
		4	150	826	1896	3477

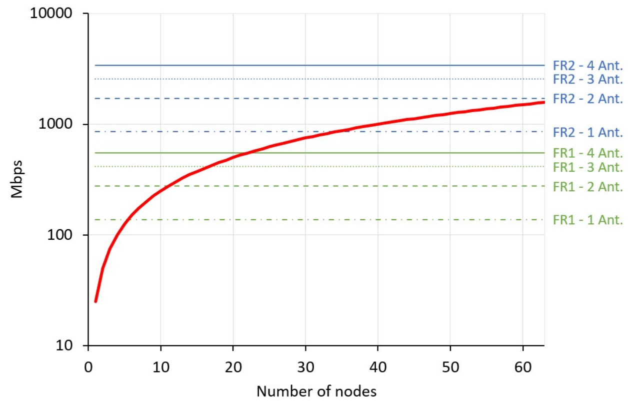

Fig. 3. Required Traffic vs 5G capacity (Uplink) - MCS 28

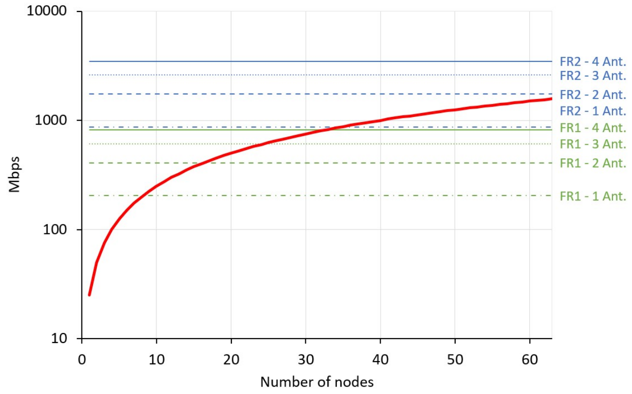

Fig. 4. Required Traffic vs 5G capacity (Downlink) - MCS 28

IV. 5G-V2X FOR WLTB

3GPP 5G Rel. 16 provides the specification of NR-V2X, the 5G extension of the cellular V2X technology. It has been designed to support the critical data capacity, latency and reliability of advanced V2X use cases, such as platooning and highly automated driving, or massive sensor exchanges. Therefore, NR-V2X communications could bring connectivity for WLTB in railway corridors where infrastructure is not available. NR-V2X aims at complementing LTE-V2X and not replacing it. Compared to LTE-V2X, NR-V2X has several salient enhancements, such as a more robust NR physical layer, unicast and groupcast communication, dynamic resource reallocation, or a new physical sidelink *feedback* channel (PSFCH) for HARQ (Hybrid Automatic Repeat Request).

NR-V2X supports two modes of operation: infrastructure V2X (mode 1) and autonomous V2X (mode 2), the latter being subdivided in 4 different autonomous scheduling strategies (mode 2a to mode 2d), enabling enhanced control on how resources can be allocated in NR-V2X.

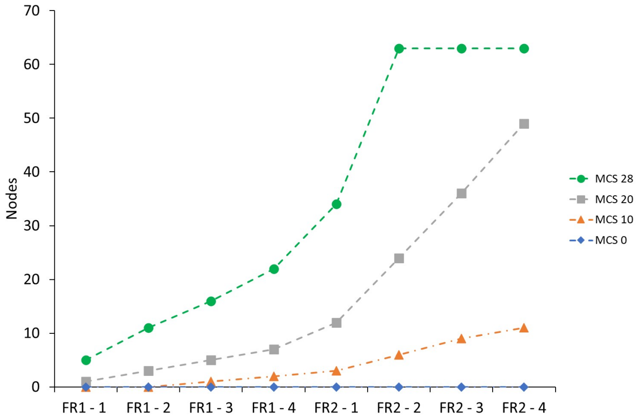

Fig. 5. Maximum network size (Uplink)

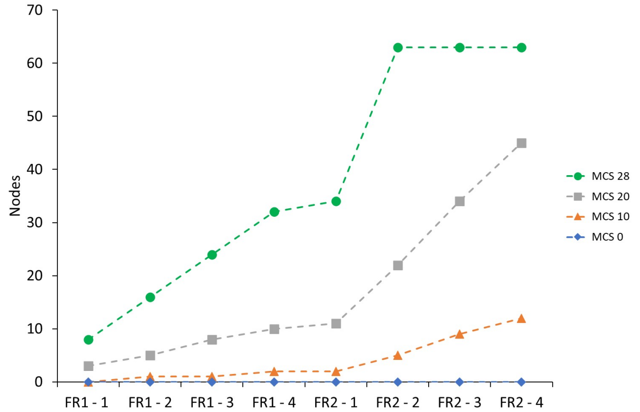

Fig. 6. Maximum network size (Downlink)

NR-V2X is expected to be beneficial for a WLTB by proposing enhanced support in the following domains:

1. *Dynamic HARQ:* supporting highly reliable HARQ communications between one or a group of consists.
2. *Long/Short term sensing & mini-slots:* supporting single-digit milliseconds resource allocations for low-latency WLTB communications.
3. *Resource preemption:* supporting the preemption of resources, and strict Quality of Service (QoS) for critical WLTB communications.
4. *Deterministic ad-hoc resource allocation:* allowing one UE to schedule resources for a group of UEs, even in the absence of 5G infrastructure.

NR-V2X is therefore expected to be a critical technology for WLTB communications. TABLE V shows the key differences between LTE-V2X and NR-V2X, together with the WLTB requirements.

V. 5G-V2X RESOURCE MANAGEMENT FOR WLTB

NR-V2X introduces four sub-modes to the NR-V2X autonomous resource allocation mechanisms (mode 2), the two most promising ones being mode 2(a) and mode 2(d). In this section, we discuss two research lines for these two modes, which could be beneficial for the WLTB: improved NR-V2X mode 2(a) with Self-organizing Time-Division Multiple Access (STDMA), as well as cluster-based scheduling NR-V2X mode 2(d).

The NR-V2X mode 2(a) corresponds to an autonomous resource allocation, and inherits from the SP-LBT (Semi-Persistent Listen-Before-Talk) scheduler available for LTE-V2X. Several studies [8] showed that such scheduler has critical limitations both in terms of reliability and resilience under heavy communication loads, but also suffers from half-duplex limitations (see Fig. 7). However, NR-V2X provides new smart mechanisms to reach reliable V2X communications, such as short-term sensing, resource pre-emption, resource reservation, and significant benefits may come from developing new schedulers. We show here the potential of a Self-organizing TDMA scheduler for NR-V2X mode 2(a). STDMA has originally been developed by [9] and standardized at ETSI as a potential alternative to the WiFi V2X CSMA-CA scheduler [10]. Several studies showed its salient features and it has been investigated also as a potential alternative scheduler for LTE-V2X [11].

As it can be seen in Fig. 8, although the SP-LBT and the STDMA schedulers have close match performance at low communication densities, the STDMA scheduler shows an increased resilience when the load (i.e. vehicle density) increases. As is also shown in Fig. 8, the 99% bound corresponds to the impact of half-duplex impairments on both schedulers. Without full duplex radio front-ends, such limitations cannot be fully cancelled, but it is possible to improve the schedulers by choosing which UE would conflict.

TABLE V. LTE-V2X , NR-V2X AND WLTB FEATURES

Requirements		**LTE-V2X**	**NR-V2X**	**WLTB**
Service Discovery		No	Yes	Yes
Group Com.		No	Yes	Yes
Multicast/Broadcast		Broadcast	Unicast/ Groupcast	Unicast/ Groupcast
Retransmission		Blind	HARQ	HARQ
Spectrum access		5.9GHz	6GHz & 60GHz	6GHz & 60GHz
Scheduling	Infra.	Deterministic	Deterministic	Deterministic
	Ad-hoc	Random	Random/ Deterministic	Deterministic
Latency		>10ms	<1ms	<1ms
Mesh		higher layer	Rel. 18,19	Required

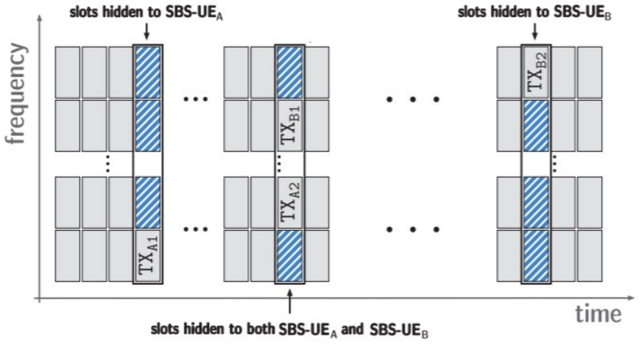

Fig. 7. Half-Duplex impairements for LTE/NR V2X, where blue packets are 'hidden' (lost) to any station transmitting on the same subframe.

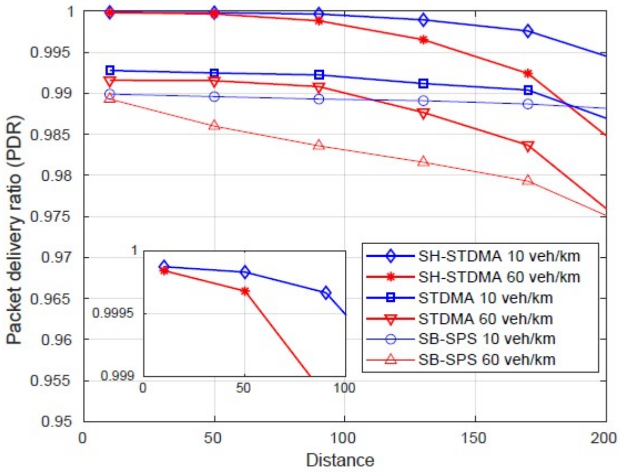

Fig. 8. Packet Delivery Ratio (PDR) comparison between SP-LBT, STDMA and SH-STDMA for different communication loads.

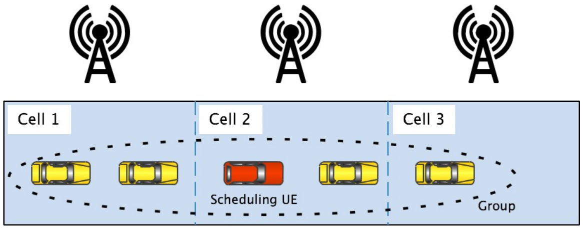

Fig. 9. 5G-V2X mode 2(d) cluster-based scheduling in a platooning scenario [12].

A recent proposal, called SH-STDMA [11], places resources conflicting from half-duplex as far away as possible, thus mitigating effective packet losses. Accordingly, SH-TDMA manages to reach ~99.9999% Packet Delivery Ratio (PDR), thus meeting one of the criteria for Ultra-Reliable and Low-Latency (URLL) V2X communications.

On the other hand, NR-V2X mode 2(d) allows UEs to select resources for other UEs, therefore enabling infrastructure reliability and dependability in an autonomous mode. However, UEs coordinating resource allocations for other UEs must select their UEs carefully, and plan the resource pools efficiently in order to avoid collisions or interferences. To address this issue, new directions are investigated, where resource allocation is carried out re-using resources depending on the geographical zone where UEs are clustered. In [12], depicted also in Fig. 9, a clear example of this proposal for vehicle platooning is shown. Following this approach, resource allocation for each working zone is different, which increases network capacity. This strategy is applicable to scenarios where several WLTBs are operating in close vicinity (e.g. stations or depots).

VI. SUMMARY

In this work the suitability of 5G technology for a Wireless Train Backbone has been analyzed. Both infrastructure-based and V2X alternatives have been explored, and theoretical analyses and simulations have been presented to indicate the performance of these technologies in high load scenarios. Obtained results indicate that 5G is a suitable technology for the WLTB, but WTLB requirements will need to be scaled down in order to cover trains with a large number of consists. Future research activities in 5G-V2X have also been outlined in the paper.

ACKNOWLEDGMENT

CONNECTA-2 and Safe4RAIL-2 projects have received funding from the European Union's Horizon 2020 research and innovation programme under grant agreements No. 826098 and No. 826073, respectively.

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