D2.3 – LTE Equipment under Challenging Wireless Scenarios – V1.2

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Abstract:	Detailed study of the impact of LTE V2X for WLTB Communications in challenging conditions. It includes a description of the test scenarios, the KPIs and the evaluation results.
Keywords:	LTE V2X, Challenging conditions, scenarios, evaluation, simulation, WLTB.

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15th January 2021 – V1.1	after JU review, updates on Executive Summary, Section 4.4 & Section 4.5, and addition of Section 5.1.
30th April 2021 – V1.2	Extended chapter 3.1.2 and 4.3.1

Disclaimer

Executive Summary

While Deliverable D2.2 - LTE Equipment: Design, implementation and impact analysis on ETBNs – describes the WLTB prototype, it does not evaluate the performance of that prototype under challenging wireless conditions, which is expected to severely impact the performance of the WLTB. Deliverable D2.3 – LTE Equipment under Challenging Wireless Scenarios - aims precisely at evaluating the performance of WLTB communications based on the 3GPP LTE V2X rel. 14 under challenging conditions. As challenging wireless environments cannot be reproduced due to safety and logistic restrictions, emulation and simulation methodologies are employed. An emulation architecture is developed from the OAI-based WLTB LTE-V2X prototype with the objective to minimize the differences between the prototype and the results from this deliverable, and for that purpose well-known simulators are used. Scenarios driving WLTB conditions challenging are proposed, followed by the simulation/emulation extensions and methodologies, and finally performance evaluations are presented and their impact on the WLTB discussed. Obtained results indicate that WLTBs based on LTE V2X rel.14 are impacted by the wireless conditions beyond the requirements of AETBN in most of the scenarios, which requires either to optimize transmit parameters and rely on mesh strategies, or to modify the OAI prototype to include non-standard extensions to the 3GPP rel.14 LTE V2X.

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Chapter 1 Introduction

1.1 Scope

In the scope of Safe4RAIL-2 WP2 activities, identified challenging WLTB communication scenarios are described in this deliverable, and the performance of the WLTB RD based on the 3GPP LTE V2X rel. 14 is evaluated. The objective is to determine the true performance of LTE V2X in railway conditions, and the fitness of this technology to CONNECTA-2 requirements.

1.2 Definitions

The table below consists of major definitions of the terms present in the document. A larger table is available in Chapter 6, providing a complete definition of abbreviations found in the document.

Table 1: Definition of Terms

Term	Definition
3GPP	3rd Generation Public Partnership
LTE	Long Term Evolution
V2X	Vehicular-to-Everything
SL	Sidelink
UE	User Equipment
eNB	Evolved Node B
EPC	Evolved Packet Core
5G	Fifth Generation Communication Systems
WLTB	Wireless Train Backbone
WLTB RD	Wireless Train Backbone Radio Device
WLTBN	Wireless Train Backbone Node
ITS	Intelligent Transport Systems
GNSS	Global Navigation Satellite System
WiFi	Wireless Fidelity
VLC	Visible Light Communication
AETBN	Adapted Ethernet Train Backbone Node

Chapter 2 Specifications of Challenging Scenarios

In this section, we will present the evaluation of the LTE V2X based WLTB in selected challenging scenarios. We selected four scenarios, comprising the majority of situations, where WLTB will be confronted:

- Busy Depot/Junction – This situation corresponds to critical coordination between consists, and subject to potentially heavy communication density.
- Train Station – This situation replicates radio conditions at train stations, where WLTB will be confronted to varying communication densities both in time and space.
- Train Track – This situation will evaluate WLTB under high speed and challenging channel conditions.
- Tunnel – This situation corresponds to WLTB under full or partial heavy tunnel channel conditions.

Before covering each scenario with more details, we first provide common parameter assumptions that will be considered throughout this document.

2.1 Common Parameters

2.1.1 Train Topology and Consist Length

According to CONNECTA2 D1.1 [1], two consist configurations can be possible: a linear topology and a mesh topology. In this document, we will focus on the mesh topology. Two train composition will be evaluated, corresponding to multiple short consists or few long consists.

- Composition 1 – this composition corresponds to a train composition made of **78 m** long consists. Accordingly, this composition will evaluate the WLTB in conditions of long WLTB wireless links, with limited mesh capabilities.
- Composition 2 – this composition corresponds to a train composition made of **26m** long consists. This composition will evaluate the WLTB in conditions of short WLTB wireless links, but with strong mesh capabilities.

According to CONNECTA2 D1.1 [1, UIC 556], the maximum train length is fixed to 850m, so Composition 1 will lead to a maximum of 10 consists, whereas Composition 2 will lead to a maximum of 32 consists.

2.1.2 Frequency Channels

As reported in S4R2, D2.2 [3], radio channels for LTE V2X WLTB radio are not specified. Officially, WLTB cannot use the channel 180/181 (5.895GHz – 5.905GHz) due to restrictions to automotive traffic safety related communications, and IEEE channels 172 and 174 are reserved for non-safety related communication. Upper channels IEEE 182/184 are so far restricted to urban rails and cannot be used by WLTB radio devices.

On the other hand, 3GPP restricts LTE V2X to operate only on C-ITS spectrum, without specifying which channel. Accordingly, this document will not comply with spectrum restriction will assume, without loss of generalities, the following frequency band:

WLTB channel – 5.895GHz-5.905GHz, 23dBm maximum Tx power

2.1.3 Packet Size and Traffic Patterns

WTLB radio devices are in charge of relaying the wireless link packets transmitted by the AETBN.

SAFE4Rail D2.2 [2] describes the packet size restrictions for LTE V2X, and a default 190 byte value is indicated. CONNECTA2 D1.1 [1] as well as Roll2Rail D2.1 [4] describes AETBN data of flexible sizes, ranging between 80 bytes up to 1432 bytes.

In terms of packet generation time, CONNECTA 2 D1.1 [1] as well as Roll2Rail D2.1 [4] propose 10ms and 20ms. Considering that the mean delay for LTE V2X rel.14 is 10-20ms, it is unlikely that these generation times are supported by LTE V2X Rel. 14 technologies. Additionally, ETSI enforces a 3% duty cycle restriction per wireless device operating on C-ITS spectrum.

Accordingly, this document will evaluate WLTB radio with packets under default 10Hz (100ms generation time) average packet generation rate and leave more stringent evaluation to further studies.

Finally, LTE V2X indicates a default MCS 6 (QPSK ½) corresponding to 6Mbps. This document will use this default value, and leave evaluation of different MCS to future studies.

In conclusion, this document will consider the following parameters for packet size and traffic patterns:

Packet size: 190 bytes

Packet generation time: 100ms

Modulation: QPSK ½

2.2 Train Station Scenario

This scenario corresponds to a highly crowded train station, where several multi-consist trains are stationary on various tracks. This scenario also considers one multi-consist trains approaching a track platform. In this scenario, it is expected that the selected moving train will experience a varying communication load, from a low channel load before entering the train station, a maximum communication load while at the train station, and eventually again a decreasing communication load while leaving the train station. It is also expected that uncontrolled interferences from non-railway LTE V2X devices might be present. Finally, the scenario also considers the potential presence of an LTE eNB/RSU as connected infrastructure capable of coordinating WLTB communications.

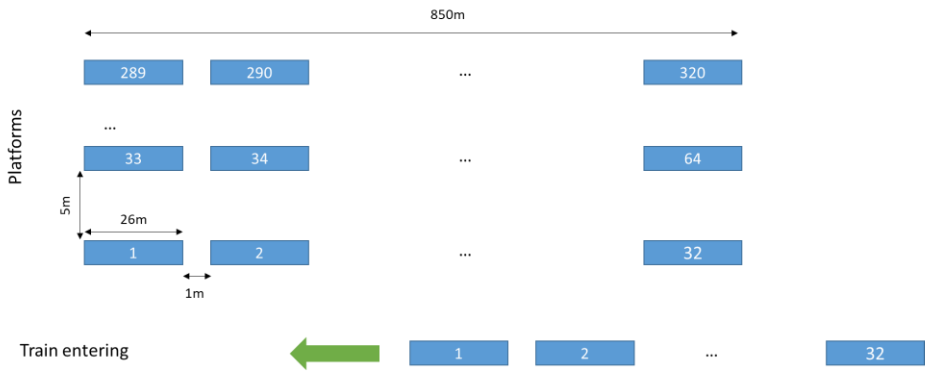

Figure 1 Train Station Scenario, 26m consist case

2.2.1 Topology & Mobility

The train station scenario will integrate the topology and mobility parameter as described on Table 2.

Table 2 Train Station - Topology

Type	Values
Topology	10 tracks, one train per track
Train Station trains	10/32 consists per train
Incoming train	10/32 consists per train
Mobility	Train station: 0 km/h; mobile train: 50km/h

2.2.2 Communication & Network Parameters

The train station scenario will integrate the following communication and network parameters, as described on Table 3.

Table 3 Train Station - Communication & Network

Type	Values
Tx Power	23 dBm
Tx Rate	10Hz
Comm. Type	Broadcast
eNB available	no

2.2.3 Channel and Propagation Models

The train station scenario will integrate the following channel model parameters as described in Table 4.

Table 4 Train Station – Channel Model & Propagation

Type	Values
Channel Bandwidth	10MHz
Channel	5.9GHz
Modulation	QPSK ½
RB/subCH	10 RB
Noise figure	9 dB
Channel Model	WINNER II B1 [12]

2.2.4 *Key Performance Indicators*

Finally, the train station scenario will evaluate the performance of the WLTB according to the PKI indicated in Table 5.

Table 5 Train Station – KPI

Type	Values
PRR	Packet Reception Ratio over distance/density

2.3 Busy Depot/Junction

This scenario corresponds to a Train Depot or a Busy Junction, with a large amount of consists located along the track and on side-tracks will need to coordinate to form a train. Compared to the Train Station scenario, this scenario is subject to a higher communication density (i.e. more consists), but does not consider the impact of mobility to the performance of the WLTB (or a negligible impact). This scenario will experience heavy consist-to-consist communication, include group-cast communication to form consist groups. However, it will not suffer from uncontrolled external interferences from other types of LTE V2X devices. The presence of an eNB is possible to assist the LTE V2X Sidelink communication.

2.3.1 *Topology & Mobility*

The busy depot scenario topology consists of a 2D lattice shaped constellation of consists. Considering the distance differences between the length of a consist (78m or 26m) and the inter-track distance (5m), communication between consists is asymmetrical on the X and Y axis, leading to potential stronger interference on the track axis compared to the consist axis. Consists at busy depots or junctions are expected to move at low speed, but without loss of generalities, we will not consider mobility at all in this scenario, considering that low speed will neither impact the topology nor the channel performance.

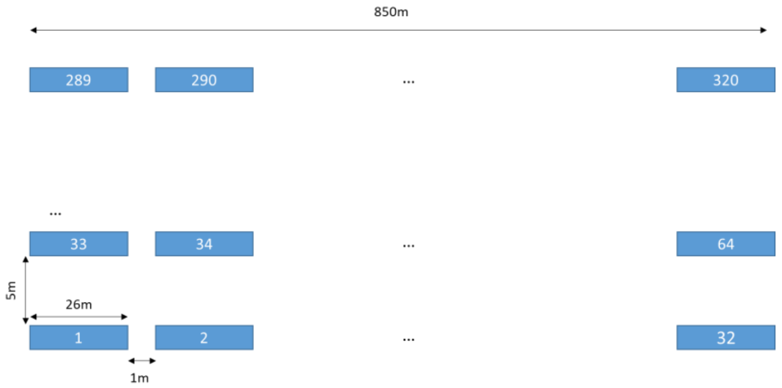

Figure 2 Busy Depot/Junction topology, 26m case

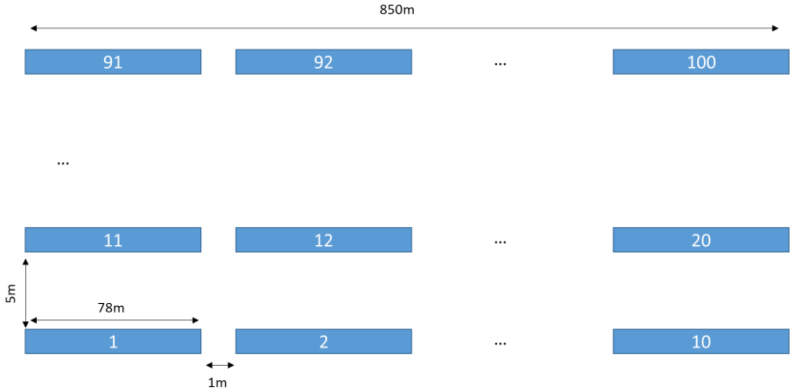

Figure 3 Busy Depot/Junction topology, 78m case

The topology and mobility parameters are provided in Table 6

Table 6 Busy Depot/Junction - Topology

Type	Values
Topology	2D lattice, tracks on the Y axis, consists on the X axis
Inter-track distance	5m
Inter-consist distance	1m
Density	10 tracks, 10/32 consists per track
Mobility	N/A

2.3.2 Communication & Network Parameters

The busy depot scenario will integrate the following communication and network parameters, as described on Table 7.

Table 7 Busy Depot/Junction - Communication & Network

Type	Values
Tx Power	23 dBm
Tx rate	10Hz
Comm. Type	Broadcast
eNB available	no

2.3.3 Channel and Propagation Models

Considering the static nature of this scenario, the channel model is going to be simpler compared to the train station scenario. The busy depot scenario will integrate the following channel model parameters as described in Table 8.

Table 8 Busy Depot/Junction – Channel Model & Propagation

Type	Values
Channel Bandwidth	10MHz
Channel	5.9GHz
Modulation	QPSK ½
RB/subCH	10 RB
Noise figure	9 dB
Channel Model	Tap delay line R2R [4], Winner II B1 [12]

2.3.4 Key Performance Indicators

Finally, the busy depot/junction scenario will evaluate the performance of the WLTB according to the PKI indicated in Table 9.

Table 9 Busy Depot/Junction – KPI

Type	Values
PRR	Packet Reception Ratio over distance/density

2.4 Tracks Scenario

This scenario corresponds to normal track-based mobility. Multi-consist trains are moving along a track and may potentially cross other multi-consist trains on the opposite track. The speed of the train (for Doppler effects) and the inter-distance between consists (in a platooning scenario) will be critical. Moreover, this scenario particularly involves high-speed mobility, which requires a channel model including the impact of Doppler and multi-path fading on the LTE V2X radio propagation. In this scenario, density is not an issue, but speed is.

2.4.1 Topology & Mobility

The track scenario consists of one or two multi-consist trains running on a track, potentially crossing one or two trains on the opposite track. Without loss of generality, speed is assumed to be constant at 300km/h, leading to 600km/h between trains in cross-tracks. The inter-distance between consists in a train is set to 1m. In the scenario of two multi-consist following each other's, the distance between the front consist and the back consist of the preceding train will be configured between 100, 200 and 400m.

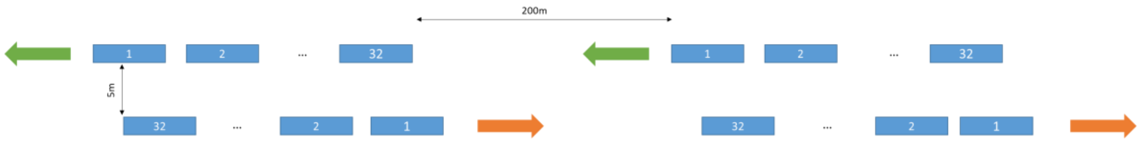

Figure 4 Track Topology, with two trains in each track direction

The topology and mobility parameters are provided in Table 10.

Table 10 Track - Topology

Type	Values
Topology	1D track
Inter-track distance	5m
Inter-consist distance	1m
Density	2 tracks, 10/32 consists per track, up to two trains
Mobility	Constant 300km/h per direction.

2.4.2 Communication & Network Parameters

The track scenario will integrate the following communication and network parameters, as described on Table 11.

Table 11 Track - Communication & Network

Type	Values
Tx Power	23 dBm
Tx rate	10Hz
Comm. Type	Broadcast

2.4.3 Channel and Propagation Models

This scenario is challenging in terms of channel propagation models, first considering the high speed and potential Doppler effects, as well as strong fast fading components due to multi-path. The track scenario will integrate the following channel model parameters as described in Table 12.

Table 12 Track – Channel Model & Propagation

Type	Values
Channel Bandwidth	10MHz
Channel	5.9GHz
Modulation	QPSK ½
RB/subCH	10 RB
Noise figure	9 dB
Channel Model	Winner II B1 [12],

2.4.4 Key Performance Indicators

Finally, the track scenario will evaluate the performance of the WLTB according to the PKI indicated in Table 13.

Table 13 Track – KPI

Type	Values
PRR	Packet Reception Ratio over distance/density

2.5 Tunnel

This last scenario models the impact of tunnels on the performance of WLTB communications. The scenario aims at considering various topologies, where a multi-consist train would be fully or partially inside a tunnel. This scenario will also include the strong changes in topology and radio interferences between a tunnel and leaving a tunnel, where more LTE V2X devices could interfere. For this scenario, various channel models considered for various tunnel topologies will be evaluated.

2.5.1 Topology & Mobility

The tunnel scenario consists of one multi-consist train running on a track, entering a tunnel, then leaving it. Speed is not a major issue, but the impact of reflections in the tunnel walls are. Also, a similar fluctuation of wireless reliability is expected when the train will leave the tunnel, facing different channel conditions and potentially an increased density of consists. From a methodological perspective, three scenarios will be considered. First, a multi-consist train fully in a tunnel. Without loss of generalities, speed will not be considered. Second, a multi-consist train, where one consist will be in a tunnel and one being outside of the tunnel, again with speed not being considered. Finally, a multi-consist train moving from a tunnel to a dense outdoor condition will be considered.

Figure 5 Tunnel topology, with a multi-consist train fully inside the tunnel

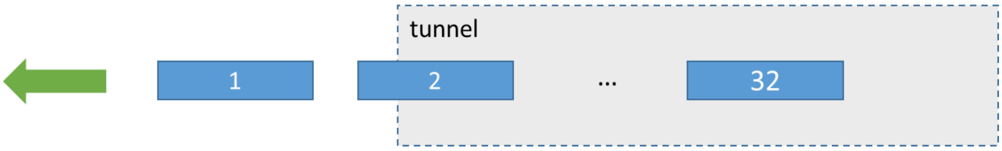

Figure 6 Tunnel topology, with a multi-consist train partially inside the tunnel

The topology and mobility parameters are provided in Table 14.

Table 14 Tunnel - Topology

Type	Values
Topology	1D track
Inter-track distance	N/C
Inter-consist distance	1m
Density	1 track, 10/32 consists per track
Mobility	N/C

2.5.2 Communication & Network Parameters

The tunnel scenario will integrate the following communication and network parameters, as described on Table 15.

Table 15 Tunnel - Communication & Network

Type	Values
Tx Power	23 dBm
Tx rate	10Hz
Comm. Type	Broadcast

2.5.3 Channel and Propagation Models

This scenario is challenging in terms of channel propagation models in a tunnel. The track scenario will integrate the following channel model parameters as described in Table 16.

Table 16 Tunnel – Channel Model & Propagation

Type	Values
Channel Bandwidth	10MHz
Channel	5.9GHz
Modulation	QPSK ½
RB/subCH	10 RB
Noise figure	9 dB
Channel Model	Tap delay line [1,2,5,7 taps] R2R [4]

2.5.4 Key Performance Indicators

Finally, the tunnel scenario will evaluate the performance of the WLTB according to the PKI indicated in Table 17.

Table 17 Track – KPI

Type	Values
PRR	Packet Reception Ratio over distance/density

Chapter 3 Simulation Platform

This chapter describes the simulation platform and the parameters of the various models available to simulate WLTB communication considering the scenario described in Chapter 2. Two simulation methodologies have been followed. First, the WLTB RD software architecture on OpenAirInterface (OAI) [6] has been extended with an emulation architecture, supporting abstraction either at the MAC layer, or at the PHY layer. A second methodology relied on using the network simulator ns-3 [8], with a LTE V2X rel.14 stack implemented. Whereas the first methodology benefits from a software architecture identical to the WLTB RD prototype (except the abstraction layers), it has limited configurability with respect to emulation parameters or mobility. The second methodology benefits from the flexibility of ns-3, but the LTE-V2X protocol stack defers from a 3GPP compliant software prototype.

3.1 OAI Link-layer abstraction

This first strategy aims at replacing the radio device (LTE V2X modem, antennas,…) by an abstraction of the radio device. Depending on the selected accuracy vs. scalability trade-off, the abstraction layer can be done at the MAC or at the PHY:

- A MAC layer abstraction, as depicted on Figure 7, will create a short-cut for any WLTB packet received by the OAI V2X architecture and reaching the MAC layer to be directly routed to the MAC layer of the target destination consist. In such configuration, OAI LTE V2X UEs are real WLTB RD, ripped off from the radio front-ends. Such MAC abstraction allows to evaluate the impact of a configurable number of extra WLTB RDs on the transmission between two real WLTB RDs.
- A PHY layer abstraction, as depicted on Figure 8, allows to integrate a full specification of LTE schedulers and only abstract PHY layer procedures as well as the channel model. Such PHY abstraction allows to emulate an arbitrarily large number of WLTB RD with their full protocol stack.

The OAI LTE V2X architecture has therefore been extended with an OAI stub and an OAI proxy architectures, depending on the options followed.

3.1.1 OAI Stub architecture

The basic strategy of the OAI stub architecture is to implement a MAC-2-MAC bypass, but also add a stub module supporting system-level PDR and Delay models. In a nutshell, any packet reaching the OAI LTE V2X MAC layer will be re-routed to the stub module, which will compute the probability to be able to deliver it to the target OAI LTE V2X MAC according to a system-level error/delay model, which is based on an analytical model of the LTE V2X rel.14 scheduler proposed in [8].

Accordingly, it is possible to emulate the reception probability of an ETBN packet over the WLTB RD, considering an arbitrarily large amount of nodes, ETBN packet sizes, ETBN transmit rates, or LTE V2X RD configurations. The limitation is that the system-level model has been validated for a single type of channel model, and that the performance evaluation of the ETBN packet under challenging scenarios are limited to the input parameters of the system-level model. The main advantage yet remains its large scalability, as it is possible to emulate the radio conditions of an arbitrarily large amount of WLTB RD.

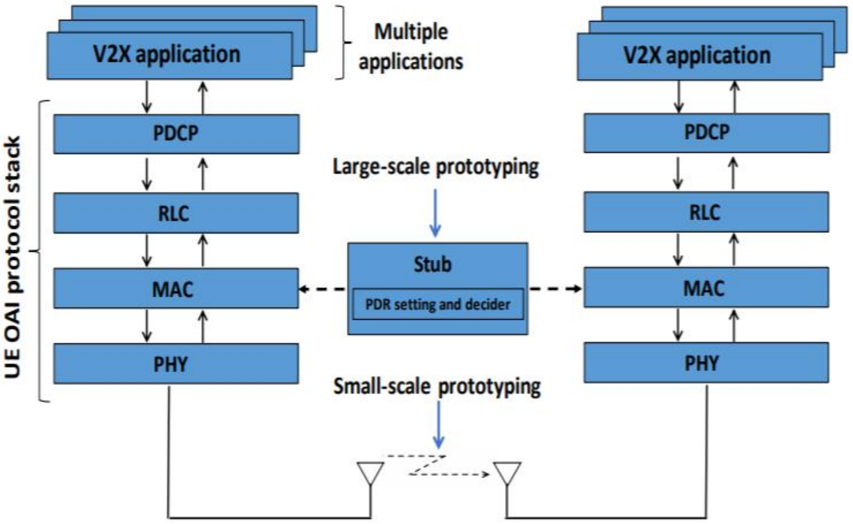

Figure 7 OAI Stub architecture, depicting the MAC-2-MAC link and the system-level module.

3.1.2 OAI LTE V2X Proxy Architecture

OAI LTE V2X Proxy architecture follows a different strategy. It radically changes the software architecture of OAI to transform it to a discrete event simulator (DES), where each OAI LTE V2X WLTB RD is considered as an independent agent, which communicates with other agents under the orchestration of the OAI Proxy.

The OAI proxy has four major functions:

- **Time master –** it overrules the OAI internal clock to synchronize any OAI agent to the same clock
- **Mobility Emulation –** it injects artificial position and mobility information to the channel emulation function. Each OAI agent has its own independent mobility data.
- **Channel Emulation –** it computes the attenuation of the OAI packet transmitted between OAI agents according to a configurable channel model. It will compute the SNR perceived by any OAI agent from an OAI transmitted packet.
- **Physical layer Emulation –** it computes the reception probability considering the impact of the channel on the OAI transmitted packet. BLER/SNR curves are used to decide if a packet at a given SNR can be received by a given OAI agent.

A salient aspect of the OAI Proxy architecture compared to the stub architecture is that it also includes a complete scheduler module, whereas the stub architecture only includes its impact within the analytical model. The LTE V2X scheduler has been integrated into the OAI Proxy architecture, and can also be replaced by different schedulers, would they respect the Proxy scheduler API descriptions.

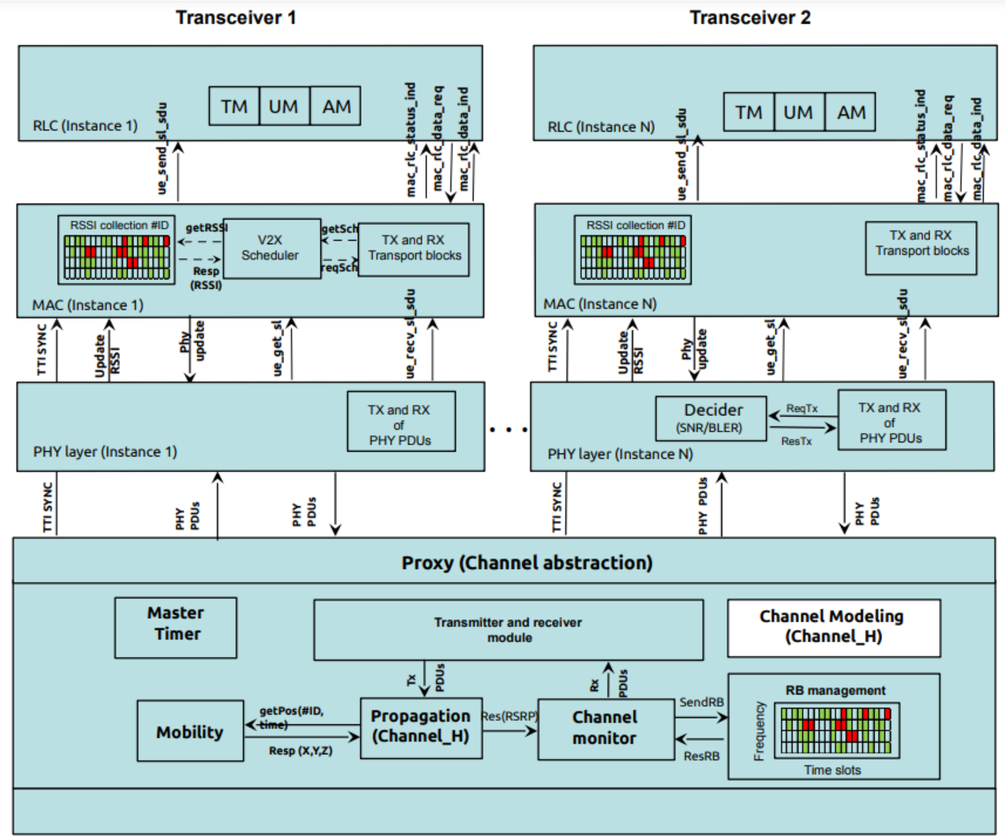

Figure 8 OAI Proxy architecture, with two OAI-based LTE V2X transceivers orchestrated by the Proxy

The Proxy architecture is not limited to orchestrating two transceivers but can also emulate a large amount of potential LTE V2X agents. However, for scalability reasons, these agents do not implement the OAI LTE protocol stack but only generate traffic and model the 3GPP LTE V2X mode 4 scheduler. The large-scale Proxy architecture is depicted on Figure 9.

Accordingly, the Proxy architecture supports three potential emulation configurations:

- **2 x Real OAI LTE V2X UE with varying channel conditions** – this configuration enables to test the impact of varying channel conditions on two OAI LTE V2X prototypes.
- **1 x real OAI LTE V2X UE with N x LTE V2X agents** – this configuration evaluates the impact of large scale traffic and interference on the OAI LTE V2X prototype.
- **N OAI V2X agents** – this configuration allows to test the performance of the LTE V2X scheduler under large-scale and configurable traffic and channel conditions.

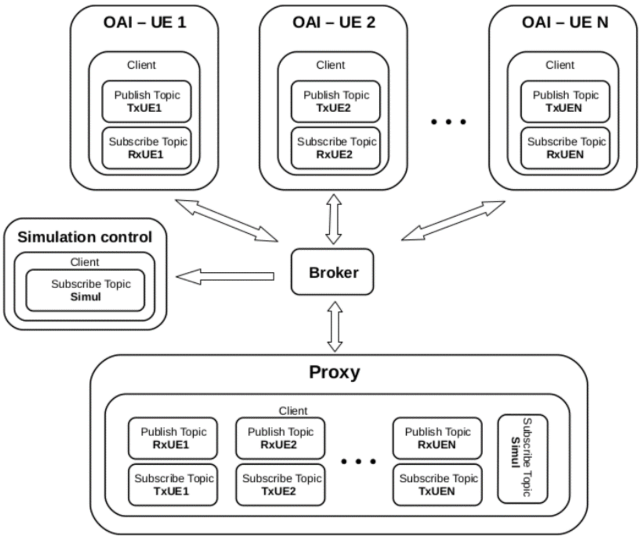

Figure 9 Multi-agent Proxy architecture emulating large-scale LTE V2X communication.

The tight integration of the Proxy architecture within OAI LTE V2X prototype therefore enables to minimize the drift between models and configurations in simulators and prototype and between demonstrators and evaluation in challenging conditions. It enables to test the exact same code (with the exception of lower LTE PHY instructions, which are emulated) either under challenging conditions or under demonstrator conditions.

3.2 The NS-3 simulation platform

The network simulator 3 (ns-3) platform is an open-source packet-level simulation platform widely adopted by the research community, and containing most of the state-of-art communication protocols, from WiFi to LTE and NR.

It is widely adopted also due to its flexible simulation framework and integrated tools for performance evaluations. To evaluate the performance of the WLTB RD under challenging scenario, we used a LTE V2X stack extension of the ns-3 LTE architecture.

3.2.1 3GPP LTE V2X Model

ns-3 natively contains a 3GPP LTE architecture and models developed by the LENA team at CTTC [9]. It has been later extended to support 3GPP LTE rel.12 D2D by the NIST [13]. And more recently, through a cooperation between EURECOM and NXP, the 3GPP LTE rel.14 V2X has been integrated [10]. Figure 10 depicts the protocol architecture of the 3GPP LTE stack in ns-3, while Figure 11 shows the added extensions to support SL communications and LTE V2X.

In ns-3, each LTE UE *netdevice* is an independent agent, which will be attached to an *Application* generating traffic. The *netdevice* will handle the channel access and ns-3 will gather all data traffic from all *netdevices* at each time step and emulate a wireless channel. At the end, ns-3 delivers data traffic to the right LTE UE agents. Mobility and Channels can be changed, either by direct control or by importing external models.

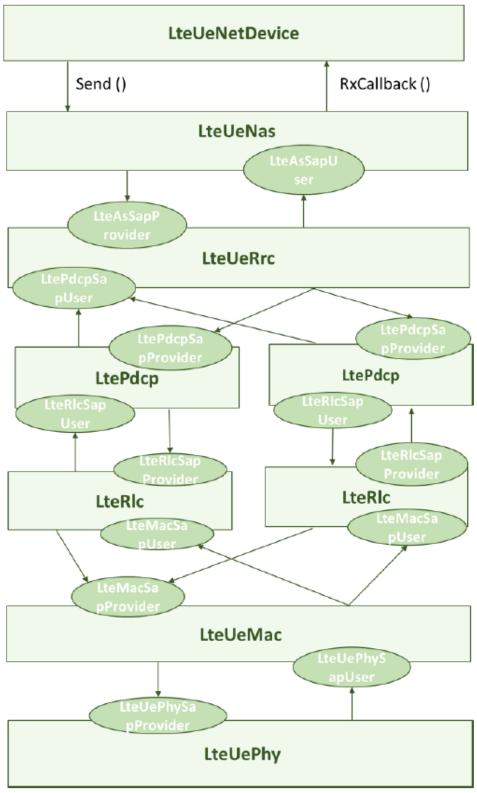

Figure 10 LTE Model in ns-3 [source: A. Mansouri, EURECOM]

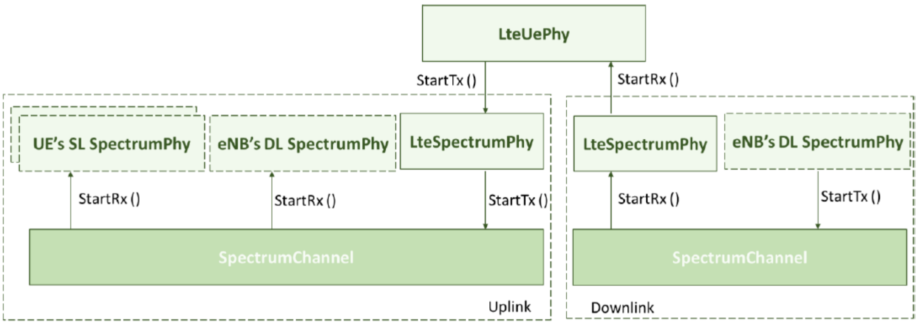

Figure 11 LTE V2X extension to support SL in ns-3 [source: A. Mansouri, EURECOM]

3.2.2 Channel Abstraction Models

ns-3 includes various channel models adapted to different wireless conditions. The most widely used ones are the AWGN or the NIST models. More recently, the 3GPP widely adopted WINNER II models have been included into ns-3. Through previous projects, ns-3 has been extended to support the WINNER II B1 (Urban Micro-cell) V2X channel model, capable of modelling channel conditions in LOS/NLOS at 5.9GHz in urban conditions.

Although WINNER II B1 is widely accepted model for evaluating LTE V2X communications, the peculiar railway environment requires to conduct additional studies with specific channel models. According to Roll2Rail deliverable D2.2 [5], a Tap Delay Line (TDL) model would be appropriate, but is not available in ns-3. This model is under development at the time of writing of this deliverable. For scenarios requiring models only available for railways (e.g. train station, tunnel), a simplified tap model has been used, considering only the attenuation component and limiting the study to 2 taps.

Chapter 4 Performance of WLTB Communication

In this chapter, we provide and analyse simulation results corresponding to the scenarios described in Chapter 2 based on the simulation platform described in Chapter 3.

4.1 General Automotive Scenario using the OAI Stub

This corresponds to an automotive scenario not described in Chapter 2, but has yet been added here as a benchmark of the performance of LTE V2X rel.14 considered in the original design space, as well as a performance indicator benchmark, when evaluating it under railway conditions.

As described in Section 3.1, the OAI Stub is able to evaluate the performance of two real OAI WLTB RD under varying communication conditions and scheduling strategies. Considering the LTE V2X rel.14 Listen-before-Talk (LBT) Semi-persistent scheduling (SPS) as scheduler and emulating an arbitrarily high numbers of potential interferes, we will be able to check the impact of challenging radio conditions on the performance of the WLTB RD.

The analytical model used for the OAI stub includes the LTE V2X LBT-SPS as well as WINNER II B1 (urban microcell) channel modelling for automotive V2X communications. All other parameters are set as in Section 2.1.

4.1.1 Simulation Results

As it can be seen on Figure 12, the Packet Delivery Ratio (PDR) heavily depends on the communication distance, as beyond 300m, it is considered to be unreliable (and already beyond 100m for high densities). Second, we can also see that the PDR also heavily depends on the traffic density. If PDR at short distance remains around 99% for 10veh/km and 60km/h, it already falls to 95% for 200 veh/km. And the impact of traffic density is more flagrant with distance, where PDR for 10veh/km at 300 remains at 98%, whereas it falls to 78% for 200 veh/km.

By zooming on short distances, Figure 13 depicts the PDR in high granularity at distances up to 250m. We can better see the true performance never reaching higher PDR than 99%, as well as the rapid drop due to increasing density, already at short distances.

Accordingly, it is clear that WLTB RD will need to favour short wireless links and adapt to traffic density. Moreover, we can see that even at short distances and low traffic density, the performance of the LTE V2X rel.14 scheduler never exceeds 99% due to half-duplex limitations in the SC-FDM receiver.

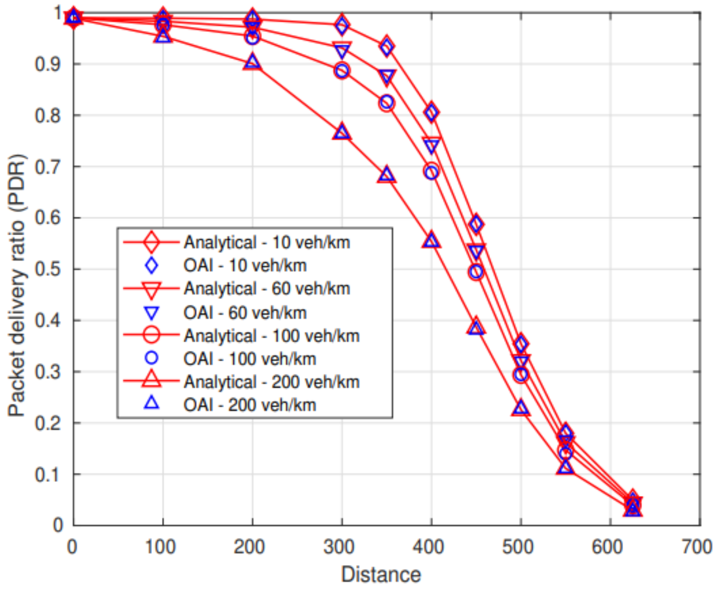

Figure 12 OAI Stub - reliability vs. distance for various traffic densities [17]

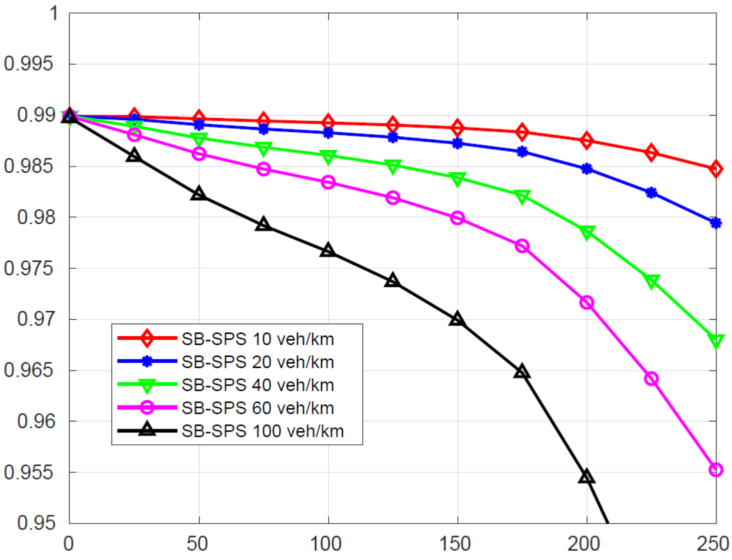

Figure 13 OAI Stub – zoom on PDR vs. distance under varying density [17]

4.2 Train Station

In this section, we evaluate the performance of the WLTB under a challenging dense train station. We also used ns-3 as simulation framework.

4.2.1 Simulation Results

In this scenario, one multi-consist train enters a train station, where multiple trains are stopped, but their WLTB will impact the WLTB of the moving train. For the performance evaluation, we compared the PRR as function of the inter-distance between the front consist of the moving train and the last consist of the static train. A 0m distance indicates they are at the same level, thus the moving train starts being impacted by the station trains. Figure 14 depicts the PRR in such situation. The figure should be read from left to right. At -900m, the moving train is too far from the train station to be impacted, and the PRR remains stable. It is to be noted that in this scenario, we computed the average PRR, considering any Tx-Rx distance and only for the moving train. Accordingly, the average PRR is approximatively 60%, as it considers also very weak PRR for large distances. Although we could also show the PRR for only short links, we believe that integrating any tx/rx distances is a better reflector of the true performance of the WLTB. And as it can be guessed, such PRR is too low, and one strategy to improve it would be to rely on shorter wireless links over multi-hops.

Figure 15 illustrates the evolution of the channel load (so the communication density) either as a function of the simulation time or the distance between the front moving consist and the train station. As it can be observed, the channel load increases significantly, but only has a marginal impact on the PRR considering all RX/TX distances. This can be explained by the fact that the weak PRR components correspond to attenuated signals, on which a higher/lower channel load does not impact much. If the long Tx/Rx components would be removed, the PRR would be increased, but on the other hand, it would be subject to more fluctuations with the channel load.

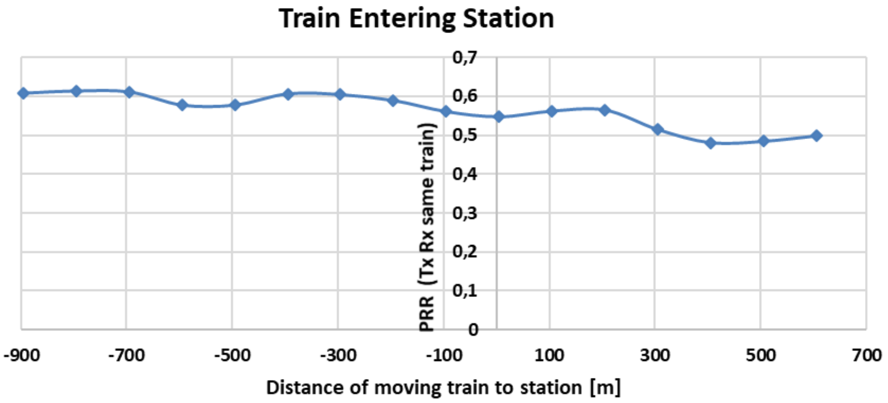

Figure 14 Train Station, PRR as function of distance; moving train perspective

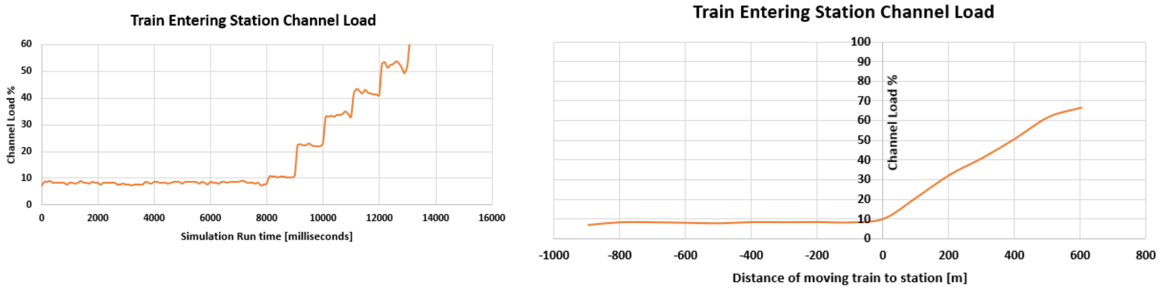

Figure 15 Train Station, evolution of the channel load (a) vs time (b) vs distance to station, moving train perspective

4.3 Depot / Dense Junctions

In this section, we provide the evaluation of the WLTB under challenging dense depot/junction conditions. For this scenario as well as all forthcoming, we used ns-3 as simulator.

4.3.1 Simulation Results

Figure 16 shows the PRR considering only one single WLTB RD transmitting. The objective is to evaluate the impact of the fading, without the contributions of packet collisions. As it can be seen, the PRR remains at 100% until 250, where the channel attenuation makes the received SNR weaker and generates packet losses.

Figure 17 considers this time all WLTB RD transmitting and accordingly includes the impact of packet collisions as well as half-duplex impairment. As expected, the PRR is significantly weaker and reaches 90% at 200m. Comparing with Figure 12, we can see that it is coherent, and makes the dense depot equivalent as an automotive domain scenario under a density of 200 veh/km. Another major observation (similar to Figure 12) is the half-duplex impairment, as the PRR is already below 100% even at short distances. Figure 18 depicts the packet loss rate only due to half-duplex. As it can be observed by comparing Figure 18 with Figure 17, the half-duplex impairment provides a 0.7% packet loss ratio and is the primary factor on the PRR at short distances. However, as it remains stable over distance, the main factor at larger distance becomes near-far terminals and collisions due to same LTE V2X resource selection.

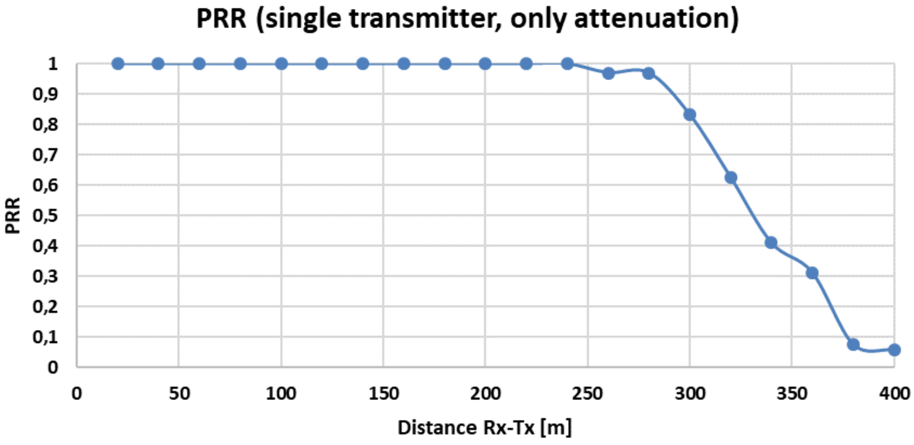

Figure 16 Dense Depot, single transmitter PRR

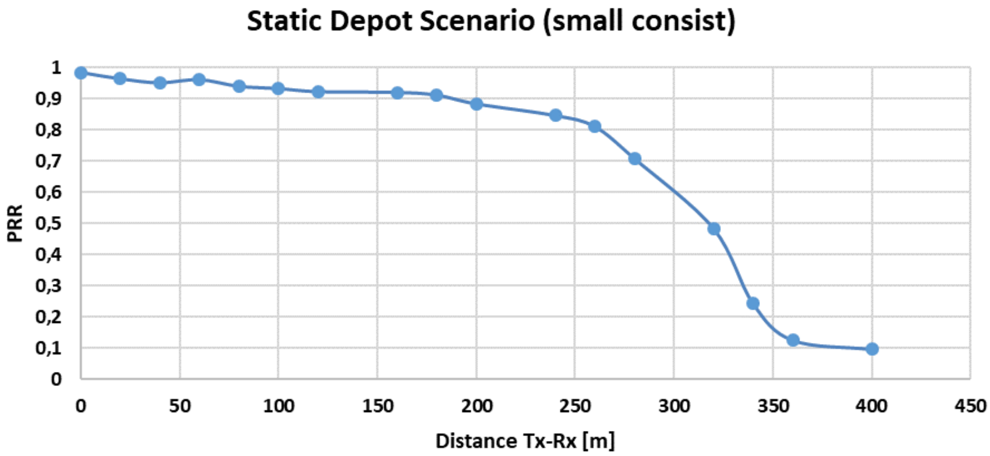

Figure 17 Dense Depot, PRR all consist transmit,

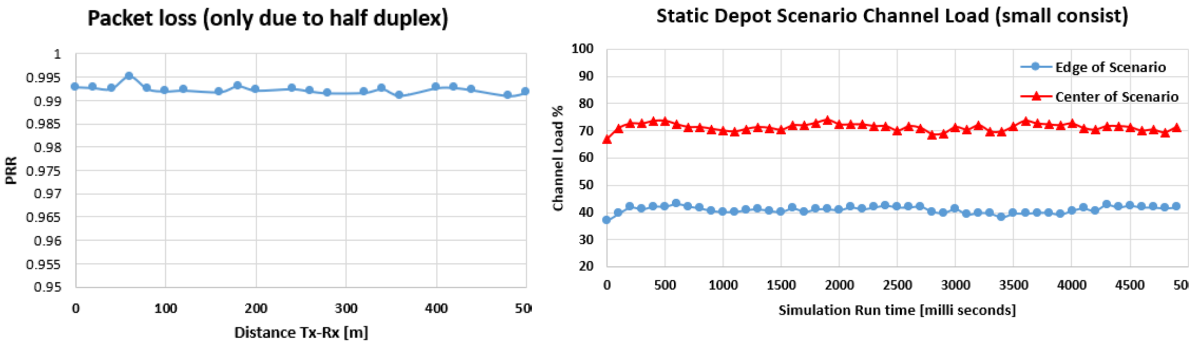

Figure 18 Dense depot, source of packet collisions; (a): half-duplex, (b) channel load

Finally, Figure 19 shows the PRR over distance for the larger consist scenario (78m long). As it can be seen, the PRR is better than for short consists (26m). This illustrates that fading has a weaker impact compared to packet collisions, and comparing it with Figure 16, the main packet loss factor is channel fading and no longer density. We can also see that with longer consists, the overall channel load is significantly lower (halved actually) compared to a shorter consist, as considering a 850m long train, shorter consists will naturally create an increased communication density.

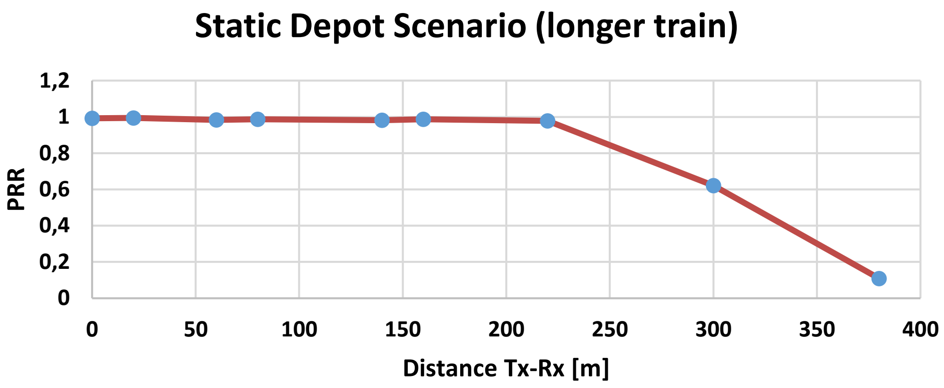

Figure 19 Dense Depot (large consist), PRR all consist transmit

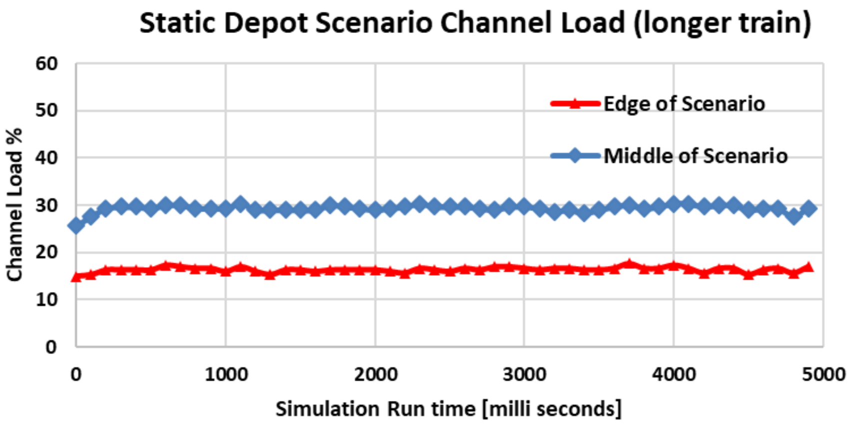

Figure 20 Dense Depot (large consist), Channel Load at centre and edge of depot

The LTE V2X technology in the train depot conditions therefore does not provide the key performances required by ETBN traffic over a *wireless* train backbone. At large and medium range, channel fading impacts reliability and at short range, near-far problems are primary sources of low performance. Considering that high reliability is only reached at short range, we also investigated the impact of reducing the transmit power and rely on multi-hop routing to relay ETBN traffic over multiple consists. The main aspect we are interested to observe is the impact of being subject to less interference and if this would manage to improve the LTE V2X reliability closer to the ETBN requirements.

On Figure 21, we evaluate the PRR as function of the distance between transmitters and receivers for three density conditions and for three transmit power selections. The three density conditions correspond to short and long consists either with 1m inter-consist distance or with 5m inter-consist distance. The smallest transmit power corresponds to reaching at most one consist. We can first see that as already observed previously, the density does not significantly impact the LTE V2X performance. This is due to the relatively long consist lengths and the spatial limitation to add more LTE V2X transceivers. However, we can see that reducing the transmit power has a significant impact on the range. By zooming at the PRR at close distance, Figure 22 unfortunately shows that no major benefit is obtained from relying on a shorter transmit power. It is actually quite the opposite and hidden terminals are negatively impacting the reliability of WLTB RD at close range (i.e. the two hops consist is hidden to the first consist), worse than if the default transmit power would be used. Accordingly, reducing the WLTB RD transmit power is not advised and the maximum allowed transmit power should be used.

This transmit power study has been also conducted to evaluate the optimal strategy for the WLTB Mesh topology. Considering that long trains may reach up to 800m, multi-hop relaying is required, but we wanted to verify if relying on more hops (at the cost of an increased delay) would be beneficial in terms of reliability. The answer is no, and the minimum amount of hops, thus a maximum transmit range, should be targeted in a WLTB mesh topology.

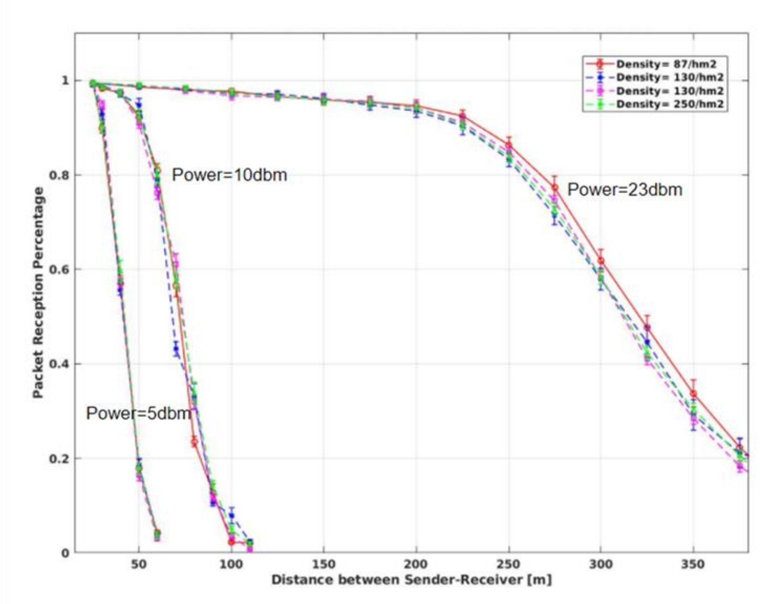

Figure 21 Impact of three transmit power levels on the reliability of the WLTB RD

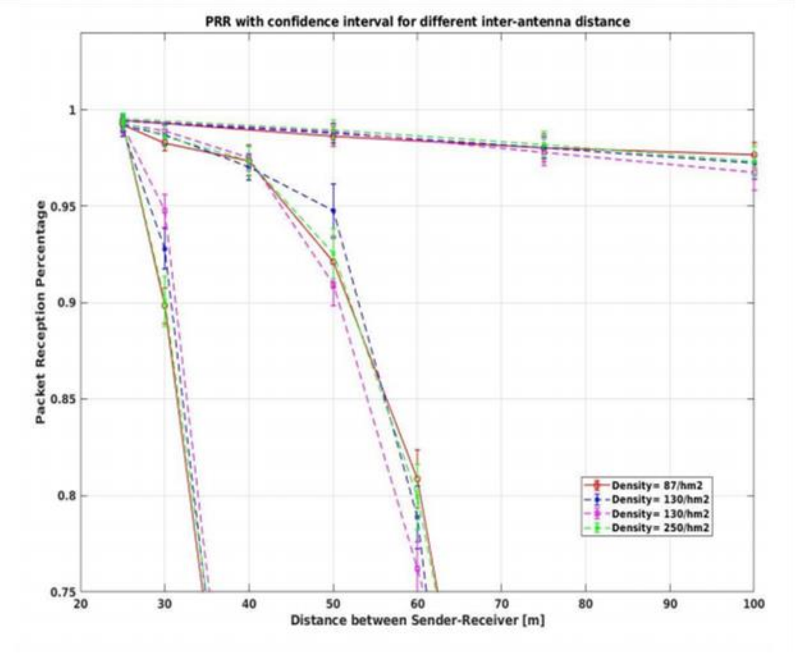

Figure 22 Zoom on the performance of the WLTB RD at close distance for various transmit power levels

4.4 Track

The track scenario will evaluate the resilience of the WLTB under strong Doppler and multipath narrowband fading. We also used ns-3 as simulation framework.

We provide here results also for approaching train-to-train communications. These results have not been obtained directly to evaluate WLTB communication, but to show the impact of approaching/passing trains on the LTE V2X rel.14 performance and varying channel load, which impacts in turn the WLTB.

4.4.1 Simulation Results

The track scenario corresponds to two situations commonly found in open tracks. Either one multi-consist train running alone on the track, where the objective is to evaluate the impact of the WLTB for inter-consist communication within the train; or two multi-consist trains are crossing each other on opposite tracks and the objective is first to evaluate the wireless link performance between front consists, as well as the impact of high-speed crossing on the inter-consist WLTB communications on both trains.

Figure 23 first depicts the PRR for inter-consist communication within the train. As it can be seen, the PRR remains stable and corresponds approximatively to the train station scenario before entering the train station. As for the previous scenario, the PRR integrates all Tx/Rx distances, leading to only a 60% PRR.

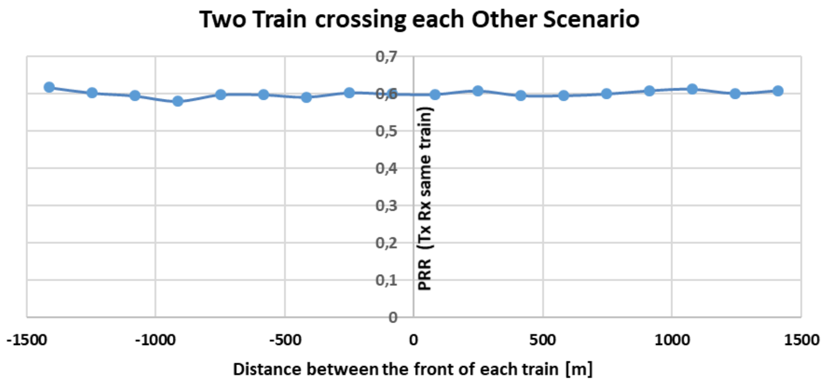

Figure 23 Track - Consist-to-Consist PRR; same train

Figure 24 shows the second situation, where two trains will cross each other, and the x-axis corresponds to the inter-distance between the front-consist of both trains. As it can be observed, at long distance, the PRR is relatively low, which illustrates a fundamental limitation in train-to-train communications. When both trains are getting nearer, then we can see that the PRR is improved until it reaches a local maximum at 62%. After passing by, both front-consists will then get away again and we see the PRR dropping again. The improvement of the PRR is mitigated by the increased Channel load as depicted on Figure 25, which models the evolution of the Channel load as function of the distance between the two front-consists. Accordingly, we can see that a stable high quality link between two opposite front consist trains is difficult, and the increase of the channel load generated while both trains are aligned on both tracks also impacts the reliability of the WLTB. One direction to improve the performance of the WLTB under this condition would be to rely on directional antennas.

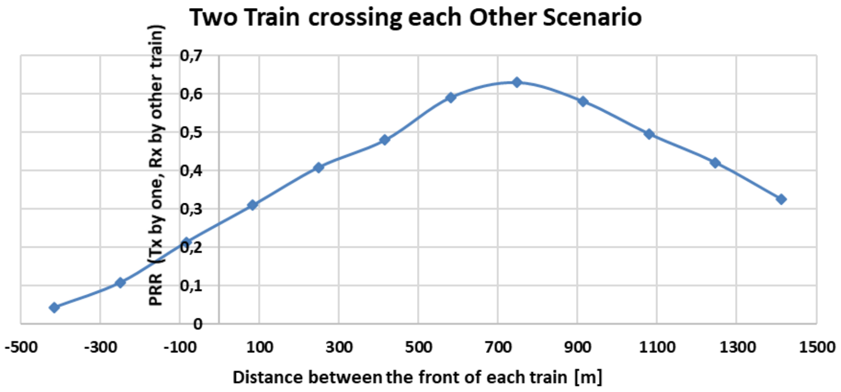

Figure 24 Track – Consist-to-Consist PRR, opposite train

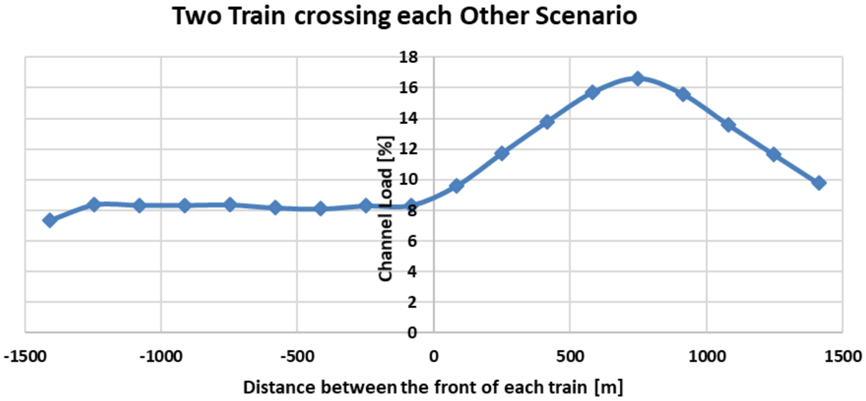

Figure 25 Track – Channel load evolution considering two train crossing on opposite tracks

4.5 Tunnel

The last scenario corresponds to a multi-consist train being in a tunnel, which are known to have challenging channel conditions. Accordingly, this scenario aims at evaluating the resilience of WLTB under varying and severe multi-path conditions in tunnel scenarios. We used a simplified Tap Delay Line (TDL) model, where we evaluated the PRR for various numbers of taps. As discussed in [16], the number of taps depends on the location of the consist in the tunnel or even the type of tunnel. We therefore evaluated 1,2,5,7 taps to cover for a wide range of potential tunnel situations.

We provide here results also for approaching train-to-train communications. These results have not been obtained directly to evaluate WLTB communication, but to show the impact of approaching/passing trains on the LTE V2X rel.14 performance and varying channel load, which impacts in turn the WLTB.

4.5.1 Simulation Results

Figure 26 first depicts the PRR as a function of distance in a tunnel. As it can clearly be seen, multi-path reflections significantly impact the PRR, as considering 1 tap (direct path), 90% PRR is reached for 280m for 1 tap, while 120m and 150m for 2 taps or 7 taps, which corresponds to a 50% loss in range for a given PRR. Taking the figure from a different perspective, at 200m the PRR for direct LOS is greater than 95%, whereas it is less than 40% for the other taps.

However, at short distances the impact of multi-path is less stringent, and for Tx ranges lower than 100m, the PRR does not differ significantly between the taps. Accordingly, in tunnel situations, short wireless links and multi-hop between consists should be preferred.

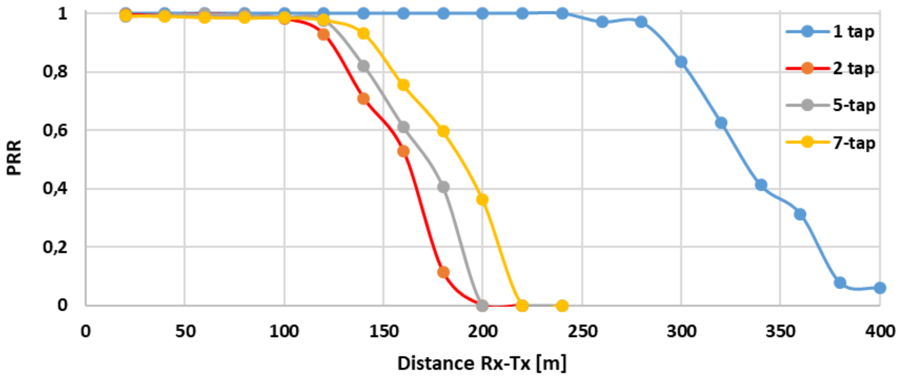

Figure 26 Tunnel scenario, ego train – PRR per tap as function of distance, short consist case

Then, Figure 27 considers the mean PRR over any consist combination within the same train (including the impact of a train crossing on a separate track). And here, we see again the impact of multi-path in the PRR drop, 60% for LOS (coherent with the train scenario) and 30% when strong multi-path is considered. This figure averages the PRR over all tx-rx distance combinations and implies that if short links can have a better PRR (as illustrated in Figure 26), some can be significantly worse. Accordingly, the WLTB should carefully select the wireless links it needs to use to reach a particular consist, and again multi-hop should be favoured.

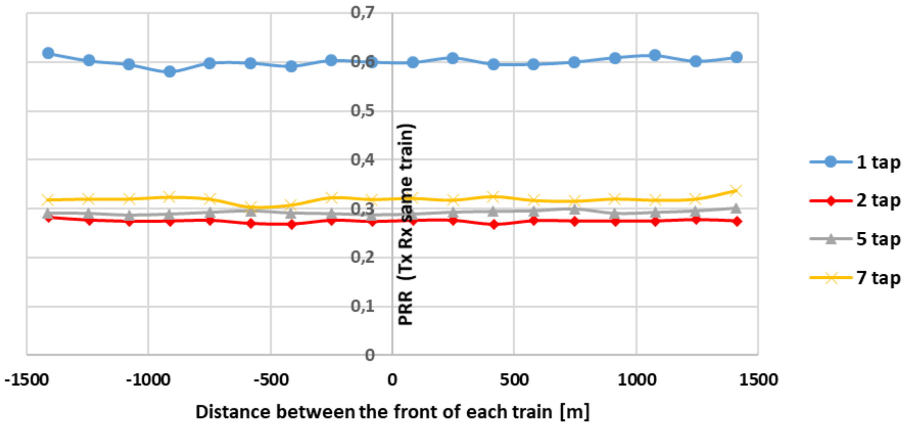

Figure 27 Tunnel, train crossing – mean PRR of ego train, as function of taps

In the next figure, we evaluate the WLTB communication between the two trains crossing in a tunnel. Figure 28 shall be read from left to right, as function of the varying inter-distance between the front consists. We can see that the PRR for any tap value follows a similar evolution, but when both trains are overlapping, we can see the major impact of multi-path, as the PRR difference between tap 1 and the other taps is significantly higher than in other inter-distances. This figure suggests that a LOS becomes more favourable for the two trains at close distances, whereas the various multi-path components are more influenced by the tunnel shape and fluctuate less. It is therefore important for two multi-consist trains needing to communicate to favour a LOS communication link, potentially via directional antennas.

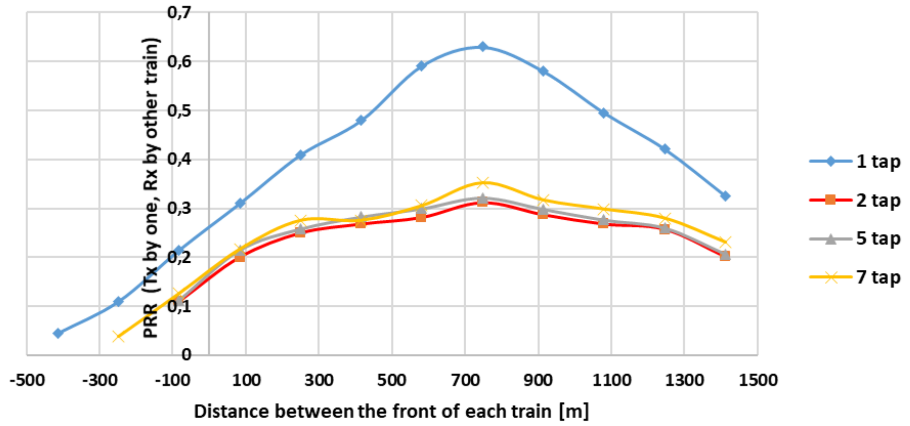

Figure 28 Tunnel, train crossing – PRR between trains, as function of taps

Finally, Figure 29 evaluates the WLTB PRR considered between the two front consists of the two crossing trains, when their inter-distance evolves between -400m to +400m (so, both trains are already overlapping, considering a train length of 850m). If a perfect WLTB PRR can be obtained on an front-consists inter-distance from 250m already for LOS, such performance will only be reached at best from 100m inter-distance considering other taps. Would two train-consist need to communicate reliably, this figure suggests again to rely on directional antennas and LOS components.

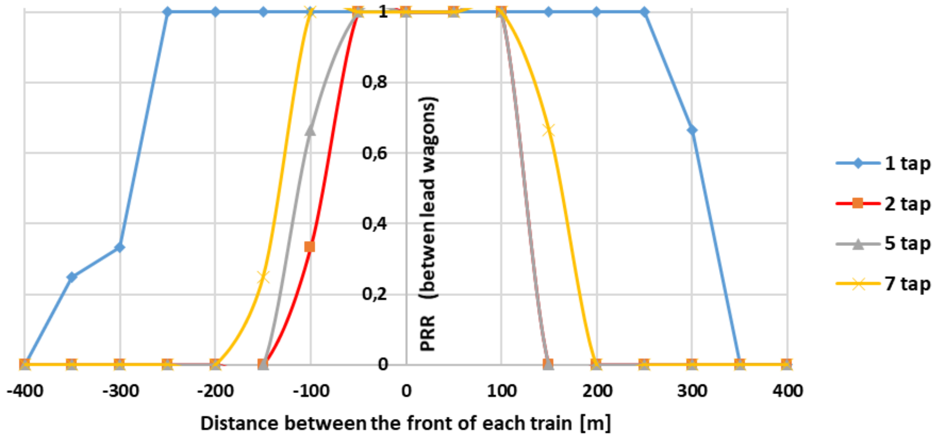

Figure 29 Tunnel, train crossing – PRR front consists, as function of taps

Chapter 5 Summary

This deliverable aimed at evaluating the performance of WLTB communications based on the 3GPP LTE V2X rel. 14 under challenging scenario conditions. We defined challenging conditions according to feedback from CTA2 to correspond to four scenarios: Busy Depot/Junction, Train Station, Track and Tunnel. The challenging conditions are specific in each scenarios (e.g. density for busy junction but multi-path for tunnel).

We first needed to develop, respectively extend, simulation platforms to conduct the evaluation. We therefore developed an Emulation architecture within OpenAirInterface capable of abstracting MAC or PHY procedures for OAI-based LTE-V2X software architectures. We also used and extended the ns-3 LTE V2X architecture for WLTB.

Second, we conducted the simulation-based performance evaluation in the four scenarios and under the specified radio conditions. The 3GPP LTE rel.14 V2X has originally being developed for the automotive domain and has been largely studied in that domain. Our studies first showed that if the 3GPP LTE rel.14 V2X keeps limitations already observed in the automotive domain, such as a systematic 1% packet loss rate due to half-duplex impairments, or the lack of reliability under heavy traffic conditions, the defined railway traffic conditions appeared to be less critical than those in the automotive domain. If LTE V2X cannot provide WLTB RD reliability higher than 99% even under favourable conditions, such value does not fluctuate much under the dense traffic density expected in the Busy Junction. However, one key observation is that the reliability of the LTE V2X technology severely drops with distance between transmitter and receiver. For instance, beyond 100m, wireless ETBN communication is not expected to be reliable. Accordingly, a multi-hop strategy will be required for WLTB, which is under study.

Another observation from the Train Station scenario is that depending on the density of consists stopped at the station, the WLTB of an incoming multi-consist train will be negatively impacted, reaching potential heavy losses that could lead to interruptions of ETBN traffic between consists. Accordingly, dynamic adaptation of LTE V2X radio access policies will need to be designed between trains in train stations and in-coming trains to mitigate this limitation.

Another conclusion of this deliverable and confirming also the state-of-art analysis of S4R2 D2.2 [3], is that the LTE V2X rel. 14 technology does not support the requirements of ETBN traffic as such. This is not specific to the railway industry as similar observations have been made also in the automotive domain [14][15].

If 5G NR V2X could be a natural target to improve the reliability of the WLTB, the LTE V2X rel.14 can still be improved either through dynamic adaptation of its communication parameters and resource allocations, or by relying on a multi-hop mesh overlay. Alternatively, different schedulers could also be evaluated for LTE V2X. These aspects are subject to current investigations.

5.1 Identified Challenges

In this deliverable, we discussed critical challenges for relying on 3GPP Rel. 14 technologies for the WLTB. We discuss in this section their implications:

- **Frequency Spectrum –** 3GPP specifies that LTE V2X rel.14 can only be used in the C-ITS frequency bands. Although the European Commission enforces technology neutrality, it restricts the usage of the various bands to specific use cases. 5.895-5.905Ghz is restricted to automotive V2X, and 5.905-5.925Ghz is currently considered for Urban Rail only. Initial discussions in ETSI TC ERM and the ITU indicated that the use cases involving sidelink communication (D2D) in Wireless TCMS are not sufficiently known, or rail stakeholders are considered to already have dedicated spectra for FRMCS (from GSM-R), implicating that it is unlikely that Wireless TCMS will be granted access to the C-ITS frequency bands, and accordingly a regulation conundrum appears with the current standardization status. This does not impact the work of the Safe4RAIL2 project, but on the long term, the FRMCS should include provisions for a dedicated V2X slidelink spectrum, or a stronger lobbying should be conducted in the ERM and ITU to support the need to be allowed to use the C-ITS frequency band for WLTB communications.
- **V2X Channel Loads and limited communication parameters** - The 3GPP LTE V2X rel.14 has been designed to operate in the same operational domain required by the Day One ETSI ITS use cases, which does not require transmit rates above 10Hz in general cases. Although it does not formally forbid it, the standardized LTE V2X rel.14 scheduler does not operate efficiently at rates above 10Hz as well, and suffers from non-negligible delays due to the need to adapt the scheduling strategy on a 20-100ms window of from previous wireless conditions. This is not coherent with the service requirements of the AETBN. If 3GPP 5G V2X (rel.16 and above) is expected to mitigate such limitations, mechanisms known as *wireless congestion control* and *data-driven scheduling* (ML/AI strategies) are options to adapt the LTE V2X rel.14 to the stringent requirements of AETBN.
- **Impact of 5G V2X (rel.16 and above) –** The Safe4RAIL2 project identified key limitations of LTE V2X rel.14 for the requirements of WLTB communications (broadcast, single group limitation, low transmit rate, single hop, etc..)as well as new 3GPP extensions within 5G that are expected to mitigate them. Although developing 5G technologies for WLTB is out of the scope of Safe4RAIL2, the consortium investigated the potential of 5G and 5G V2X (rel.16 and above) for Wireless TCMS, WLTB and WLCN. More details will be described in Deliverable D2.4 - Advanced Wireless Technologies and Applications for Wireless TCMS. Yet, LTE V2X rel.14 is also expected to be improved by a better adapted scheduler and the Safe4RAIL-2 consortium evaluates its replacement by a TDMA approach.

Chapter 6 List of Abbreviations

Abbreviation	Explanation
API	Application Programming Interface
COM	COMmunication
CTA	CONNECTA
CS	Consist Switch
D2D	Device to Device
DbD	Drive-by-Data
DL	Downlink
ECN	Ethernet Consist Networks
ECU	Electronic Control Unit
ED	End Device
ETB	Ethernet Train Backbone
ETBN	Ethernet Train Backbone Node
HW	Hardware
LBT	Listen-Before-Talk
LTE	Long Term Evolution
MAC	Media Access Control
MoCC	Model of Computation and Communication
NG-	Next Generation (TCN/TCMS)
NIC	Network Interface Card
NTW	Network
NR	New Radio
OCB	Outside the Context of a BSS
OEM	Original Equipment Manufacturer
PDR	Packet Delivery Ratio

Abbreviation	**Explanation**
PHY	Physical Layer (Transceiver)
ProSe	Proximity Services
RD	Radio Device
S4R	Safe4RAIL
SIL	Safety Integrity Level
SL	Sidelink
SPS	Semi-Persistent Scheduling
SRC/DEST	Source/Destination
SW	Software
TCMS	Train Control and Management System
TDMA	Time Division Multiple Access
TSN	Time-Sensitive Networking
Tx/Rx	Transmitter/Receiver
UL	Uplink
UDP	User Datagram Protocol
V2X	Vehicle To Everything
WLTB	Wireless Train Backbone
WP	Work Package

Table 18: List of Abbreviations

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