D2.2 – LTE Equipment: Design, implementation and impact analysis on ETBNs

Project number:	826073
Project acronym:	Safe4RAIL-2
Project title:	SAFE architecture for Robust distributed Application Integration in roLling stock 2
Start date of the project:	1st October 2018
Duration:	31 months
Programme:	H2020-S2RJU-OC-2018

Deliverable type:	Demonstrator
Deliverable reference number:	ICT-826073 / D2.2 / DRAFT | 0.1
Work package	WP 2
Due date:	May 2020 – M20
Actual submission date:	3rd January 2020 (interim)

Responsible organisation:	EURECOM
Editor:	Jérôme Härri
Dissemination level:	Public (interim)
Revision:	DRAFT | 0.2

Abstract:	Description of the design and implementation of the LTE equipment as WTBN radio.
Keywords:	Requirements, Design, LTE V2X, ProSe, WLTB, Prototype, Demonstrator

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 826073. The information and views set out in this document are those of the author(s) and do not necessarily reflect the official opinion of Shift2Rail Joint Undertaking. The JU does not guarantee the accuracy of the data included in this article. Neither the JU nor any person acting on the JU's behalf may be held responsible for the use which may be made of the information contained therein.

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Executive Summary

The Deliverable D2.2 – LTE Equipment: Design, implementation and impact analysis - aims at describing the architecture of the LTE V2X rel. 14 based WLTB radio. Stemming from the WLTB requirements identified in D2.1, this deliverable first provides a state-of-the-art overview of potential wireless and mesh technologies for the future WLTB, and compare it against the requirements in D2.1. Based on this, and in coordination with the CFM project, this deliverable will motivate the technology choice and the WLTB architecture selected by S4R2 both for the demonstrator and for research-oriented extensions towards 5G. This deliverable also provides a description of the OpenAirInterface™ LTE-V2X Rel.14 software and hardware architecture design for the WLTB radio, including additional functionalities required by the identified requirements in D2.1 but not supported by LTE-V2X Rel. 14.

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Chapter 1 Introduction

1.1 Scope

In the scope of Safe4RAIL-2 WP2 activities, the components that make up the Wireless Train Backbone radio are described in this document. The objective is to determine which technology should be the most suitable one for final WLTB products and for the CONNECTA-2 demonstrator.

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.

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 Interfaces	Wireless Train Backbone Node
ITS	Intelligent Transport Systems
GNSS	global navigation satellite system
WiFi	Wireless Fidelity
VLC	Visible Light Communication

Table 1: Definition of Terms

Chapter 2 Access Technologies State-of-Art

2.1 LTE ProSe (V2X,D2D)

The ProSe technology is an extension of LTE supporting Device-to-Device communication. The following section provides a brief overview of the key features.

2.1.1 Bit rate

The LTE ProSe introduces a new Sidelink (SL) for D2D communication, which borrows the Uplink (UL) resources and as such is restricted by its capacity limitations. SL resources are gathered in aggregated pools that can be continuous or spread in the UL resources, therefore allowing for different SL pools to have different types of services or enable resource reuse. However, the size of individual SL resource pools are related to the number of different SL pools as well as the resources left for UL. In LTE-V2X mode 4 (ad-hoc), UL resources are not used and the SL pools may span over the total 10Mhz bandwidth and the full frame duration.

A sidelink pool is also called a SL channel and is decomposed in multiple different SL sub-channels. 3GPP LTE specification 36.213 defines the following possible subchannel sizes: 4, 5, 6, 8, 9, 10, 12, 15, 16, 18, 20, 25, 30, 48, 50 RB, and the possible number of subchannels: 1, 3, 5, 10, 15 or 20. One ITS station can use one or multiple subchannels to transmit its data. Accordingly, a maximum amount of 50RB per subframe is available, although half-duplex issues will effectively reduce its capacity.

LTE ProSe supports various modulation (MCS), ranging from BPSK to 64QAM, which coding rate is directly related to the channel and sub-channel mapping. Ignoring half-duplex limitations, 50RB could be allocated using either BPSK or 64QAM, leading to a theoretical similar capacity between 3-27Mbps. However, LTE-V2X involved a control overhead that can reach up to 50%, thus dividing up to half the effective capacity. Finally, half-duplex should also be considered, which in a 3-subchannel per subframe, would lead to the loss of 1/3 of the subframe capacity (as a UE transmitting on one subchannel could not listen to the other two), which can reach up to 1/3 of the total capacity, would the UE choose to transmit on each of the suframe in the given SL resource pool.

The ETSI ITS suggests an optimal configuration for the LTE-V2X of a 10Mhz SL pool, divided in 3 subchannels of 16 RB per subframe, modulated according to QPSK 1/2 , which leads to a capacity around 6Mbps. This yet assumes a fixed packet size of exactly 191 bytes, a lower size leading to padding and a higher size leading to severe half-duplex limitations.

MCS #	Modulation, Coding Rate	RB Pairs	Min. SINR [dB]	Range [m] (only PL)	Subch. Size	Packets per TTI
0	QPSK, 0.13	86	−2.83	418	5	-
1	QPSK, 0.17	66	−1.38	411	5	-
2	QPSK, 0.21	54	−0.22	404	5	-
3	QPSK, 0.27	41	1.49	392	5	1
4	QPSK, 0.33	34	2.76	382	6	1
5	QPSK, 0.41	28	4.40	365	5	1
6	QPSK, 0.48	23	5.79	354	5	2
7	QPSK, 0.57	20	7.30	336	6	2
8	QPSK, 0.65	18	8.60	320	5	2
9	QPSK, 0.73	16	9.88	306	6	2
10	QPSK, 0.82	14	11.16	294	6	2
11	16QAM, 0.41	14	11.16	294	6	2
12	16QAM, 0.46	12	12.83	278	5	3
13	16QAM, 0.52	11	14.46	258	5	3
14	16QAM, 0.59	10	16.39	237	6	4
15	16QAM, 0.67	9	18.73	213	6	4
16	16QAM, 0.72	8	20.05	203	5	5
17	16QAM, 0.75	8	21.10	191	5	5
18	16QAM, 0.84	7	23.54	172	5	5
19	16QAM, 0.92	7	25.93	150	5	5
20	16QAM, 1.00	6	28.10	137	5	5

Figure 1 LTE-V2X Modulation Table [source: Bazzi et al. Survey and Perspectives of VehicularWi-Fi versus Sidelink Cellular-V2X in the 5G Era]

2.1.2 Time considerations

The LTE ProSe does not specify any specific scheduler for the D2D resource allocation. However 3GPP provides a default LTE V2X (rel. 14) mode 4 scheduler based on a Listen-before-Talk and Semi-persistent scheduling. The algorithm allocates resources on a 1-ms subframe basis (i.e. a packet having less than 1ms airtime will need to be padded to match 1ms airtime), and according to a 20ms-100ms long term sensing over a 1000ms historical sensing. This concretely means that a UE cannot allocate resources before having sensed the channel for at least 20ms up to 100ms. This is due to the fact that a UE needs to identify all occupied and available sub-channels in order to avoid collisions. Accordingly, in worst case scenario (still assuming the availability of at least one sub-channel), the LTE-V2X transmit delay reaches between 20ms to 100ms.

As depicted in Figure 2, a WLTB RD must first sense the wireless channel for a 1 second sensing period, and then it will select wireless resources within a 100ms selection window. A WLTB RD may only select wireless resources within that window having a RSRP lower than a target threshold. Accordingly, near-far problems may cause packet collisions between different WLTB RD.

The LTE V2X (rel. 14) in mode 4 uses a Semi-Persistent Scheduling approach particularly tailored for periodic type communications. Resources may be reserved for 1, 3, 5, and 7 potential transmissions, before a LBT reselection must be performed. However, SPS on a LBT strategy may also increase potential collisions over multiple transmissions unless a LBT reselection is performed.

Considering that sub-channel availability or even semi-persistence in the allocated resources, collision may occur and such delay cannot be guaranteed.

All default parameters are set in a static configuration file, which the LTE V2X device will load. In mode 1 or 3 (on-network), this configuration file may be overwritten by the configuration parameters set by an eNB.

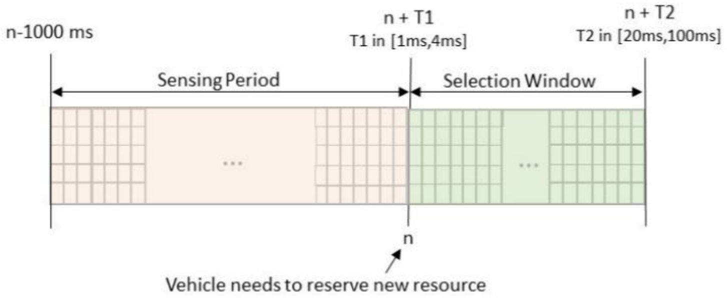


Figure 2: LTE V2X sensing and resource selection procedure

2.1.3 Robustness/Interferences

The LTE Prose (D2D/V2X) are both based on OFDM modulation mitigating narrow-band interferences, but highly sensitive to Doppler spread and channel coherence times. Accordingly, small packets with airtime less than 1ms are suggested, yet considering the LTE ProSe 1ms subframe limitation, LTE D2D/V2X is expected to be subject to short channel coherence time, typically found in highly dynamic environments. Accordingly, a robust coding scheme (QPSK and lower) would be required, as well as retransmission schemes (e.g. HARQ). Different from LTE D2D, LTE-V2X does not support HARQ, thus exposing it to severe packet losses in highly dynamic railway environments.

LTE D2D is not restricted to a specific channel, but LTE-V2X must operate on the ITS band (5.9Ghz). A the time of writing, it is expected that the LTE-V2X will need to coexist with the ITS-G5/DSRC technologies, leading to strong co-channel interferences. The exact impact of such co-existence is not well known and is currently under investigation. Yet, considering both LTE-V2X and ITS-G5 technologies both at steady-state and with uniform distribution of the bit-load in the 10MHz channel bandwidth, a 50% mutual-interference could be easily imagined.

Moreover, although the LTE-D2D does not clearly indicate the type of antenna, the LTE-V2X suggests omni-directional antennas. Accordingly, LTE-V2X can also be subject to cyber-physical attacks and jamming, leading to inoperable LTE-V2X/D2D communications.

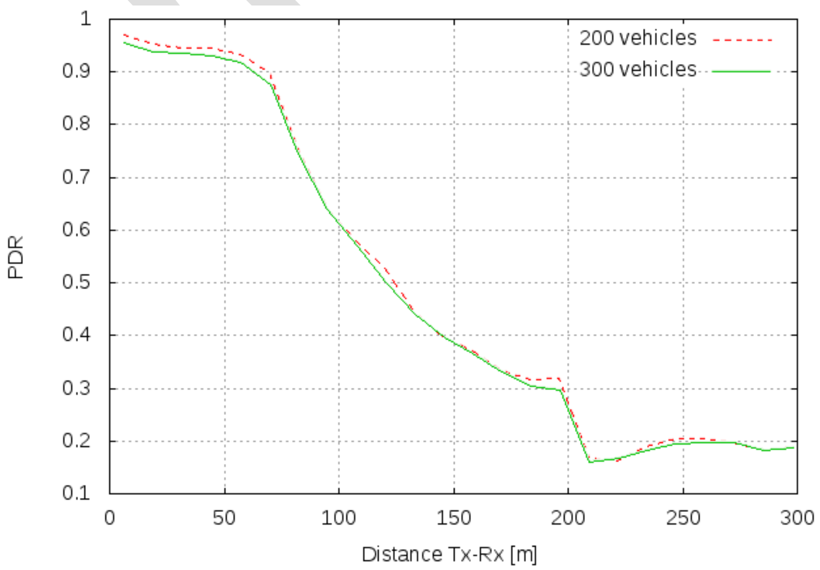


Figure 3 PDR vs Distance Tx-Rx for 200, 300 vehicles (speed = 50 km/h) in urban scenario

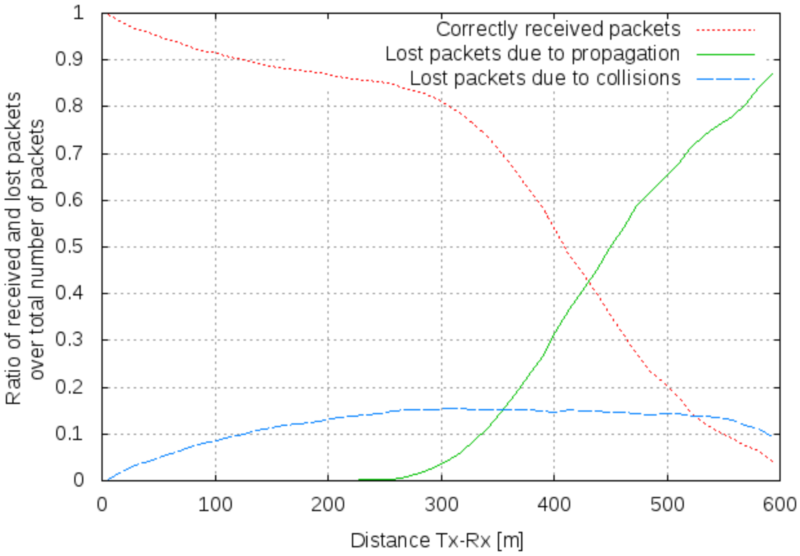


Figure 4 Ratio of received and lost packets over number of sent packets for 200 vehicles in slow highway scenario

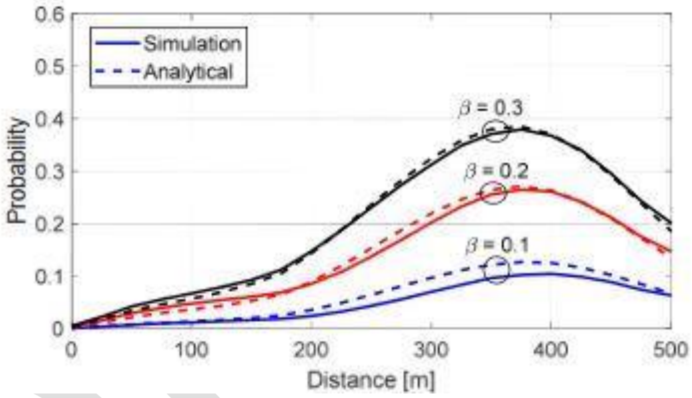


Figure 5 Probability of packet loss due to collisions as a function of the distance between transmitter and receiver (Pt=20dBm, λ=10Hz, 4 sub-channels/sub-frame (QPSK 0.7) and different traffic densities (0.1;0.2;0.3vhl/m). [source: Manuel Gonzalez-Martin, Miguel Sepulcre, Rafael Molina-Masegosa, Javier Gozalvez, "Analytical Models of the Performance of C-V2X Mode 4 Vehicular Communications"]

2.1.4 Practical considerations

Even though the LTE ProSe D2D was already specified in LTE Rel.12, D2D chipsets are at the time of writing not available. However, the critical automotive market led to an acceleration of the release of LTE Rel.14 V2X capable chipsets. Several chip manufacturers announced the availability of LTE-V2X boards as early as end 2019.

However, the LTE-V2X technologies is strongly interleaved in the higher layer stacks (at least in Europe), for instance to provide security mechanisms as the LTE-V2X does not include a SIM card. The ETSI ITS is in the process of extending the ETSI ITS stack specification for LTE-V2X, an effort which is not expected to be completed before mid-2020. Accordingly, LTE-V2X boards will not be commercially available before 2020 at best.

The LTE-V2X Rel.14 technology allows two modes of operations: pure ad-hoc (mode 4) and infrastructure assisted (mode 3). While the ad-hoc mode will allows a WLTB operation in the absence of infrastructure (LTE eNbs), the presence of LTE eNBs and 5G gNB (e.g. replacing GSM-R or on train stations and depots) will allow the WLTB to be coordinated by the infrastructure and to perform better under challenging conditions.

2.2 ITS-G5 (a.k.a DSRC)

The ETSI ITS-G5 is the WIFI (IEEE 802.11) technology supporting device-to-device communications for the transportation domain. The following section provides a brief overview of the key features.

2.2.1 Bit rate

The ITS_G5, also known as DSRC in the USA, originates from the IEEE 802.11p amendment, which is based on the IEEE 802.11a PHY, As such, ITS-G5 has an OFDM PHY, well adapted to mitigate narrow-band interferences. In order to further mitigate a longer channel delay and Doppler spread, the IEEE 802.11p operating in 'half-clock' in a 10Mhz bandwidth and accordingly, slashed the IEEE 802.11a bit rate by half (max capacity 27Mbps instead of 54Mbps).

2.2.2 Time considerations

The IEEE 802.11p MAC, on which the ITS-G5 is based, is based on a contention-based mechanism known as CSMA-CA, which means that channel access delay is not bounded and depends on the number of contending stations. However, different from LTE-V2X, which is limited to a 1ms granularity (1 LTE subframe), ITS-G5 has a 9µsec slot time and accordingly has a more dynamic channel access time.

However, the ITS-G5 requires to comply with a wireless congestion control strategy, which aim (in the EU) is to shape traffic according to a leaky-bucket strategy. In other words, the ITS-G5 under DCC will have a limited packet generation rate as function of the number of contending stations. In a worst situation, such traffic shaping is expected to increase the channel access time up to 1000ms, as illustrated on Figure 6.

State	CBR	Packet rate	T_{off}
Relaxed	< 30 %	20 Hz	50 ms
Active 1	30 % to 39 %	10 Hz	100 ms
Active 2	40 % to 49 %	5 Hz	200 ms
Active 3	50 % to 65 %	4 Hz	250 ms
Restrictive	> 65 %	1 Hz	1 000 ms

Figure 6 DCC Toff table [source: ETSI TS 102687]

2.2.3 Robustness/Interferences

ITS-G5 being based on OFDM, it is resilient to narrow-band interferences, but sensitive to Doppler spread and channel coherence times. Accordingly, small packets with airtime less than 1ms are suggested. Accordingly, a robust coding scheme (QPSK and lower) would be required, as well as retransmission schemes (e.g. HARQ). And as any contention-based strategies, the robustness of the ITS-G5 technology depends on the number of contending station and is therefore stochastic.

2.2.4 Practical considerations

ITS-G5 is a mature technology, available since 5 years already. Technologically different from LTE V2X, ITS-G5 provides a similar performance in practical contexts. Its major drawback is its lack of natural integration into a global cellular systems, and a performance not compliant with Time Sensitive Networking requirements.

Due to the lack of strict QoS, but from its agile multi-user multi-environment management, it is a serious technology option to WLTB, if weaknesses such as CSMA-CA could be replaced by deterministic ad hoc schedulers.

Moreover, irrespectively from its potential performance and availability, ITS-G5 unfortunately lacks a natural integration in the cellular (GSM-R, LTE-R) systems, where it could not be assisted by an existing infrastructure to improve its performance towards TSN.

2.3 NR V2X

2.3.1 Bit rate

The target bit rate for NR V2X is not fully clear at the time of writing, notably due to the lack of advanced prototypes. However, NR V2X is a 5G technology, and as such, it should reach the 5G target bit rate:

- **Middle Band (sub 6Ghz)**: < 2-3 Gbps
- **Higher Band (>20Ghz)**: < 20Gbps

2.3.2 Time considerations

LTE V2X has two major weaknesses in terms of delay. First, the LTE V2X LBT (Listen-Before-Talk) SBS (Semi-Persistent-Scheduling) requires to select resources over a 20ms time windows, and assuming a 100ms resource statistic history. Although the 5G NR does not have a dedicated scheduler (at the time of writing), it is expected that it will no longer be based on a LBT (Listen-Before-Talk) strategy but on a dedicated coordination benefiting from the new scheduling functions (see Figure 7).

Second, a LTE V2X slot is 1ms, which means that regardless of the message size, it will occupy 1ms time. Considering that most of the V2X messages are approximatively 500 μs and a limited number of messages allowed in frequency (usually 2), E2E delay can grow beyond what is required for time sensitive communications. NR V2X introduces the concept of mini-slot, which jointly with a more flexible frequency usage (15kHz, 30kHz, 60kHz) provides sub-ms subframe time.

Along with a flexible control resource blocks, NR V2X aims at providing 1ms delay.

2.3.3 Robustness/Interferences

NR V2X has several improvements in terms of robustness and interference. The first one is the possibility to reserve retransmission opportunities to mitigate the impact of collisions as depicted on Figure 7. LTE V2X also support retransmissions (called semi-persistent scheduling) but it has been designed to reduce the scheduling delay overhead as well as to improve the receiver gain to increase communication range. LTE V2X could not optimize retransmission based on reception or non-reception of messages.

In order to fully take benefit of this retransmission option, NR V2X provides another innovation called NACK (i.e. Negative Acknowledgments), where messages scheduled but not received by V2X receivers would allow to notify the transmitter, thus enabling the retransmissions.

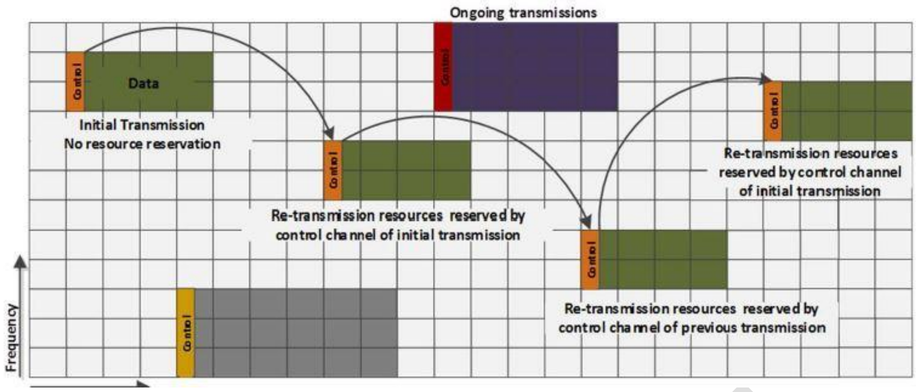


Figure 7 NR V2X Retransmission Reservation [source: 3GPP Tdoc R1-1902997 Qualcomm]

Finally, the third innovation of NR V2X is an increased flexibility in the scheduling support. The NR V2X ad-hoc mode, called mode 2, is decomposed in 4 sub-groups:

- **Mode 2(a) Autonomous resource selection –** same as LTE V2X mode 4
- **Mode 2(b) UE assists resource selection of other UEs –** a UE may indicate its preferred resources to other UEs
- **Mode 2(c) UE is configured with sidelink grants –** same as LTE V2X mode 4 SPS
- **Mode 2(d) UE schedules sidelink transmission of other UEs –** a cluster-head UE directs V2X communications, like LTE V2X mode 3, yet without eNB

2.3.4 Practical considerations

NR V2X is an evolution of LTE V2X, correcting most of its weaknesses identified for future automated robotics. The 3GPP NR V2X is expected to be frozen by the end of 2019, with the first available devices commercially available no earlier than 2025.

Considering the requirements identified in D2.1 for the WLTB, 5G V2X is the technology providing the maximum match. Not being available at the time of the S4R2 project, the LTE V2X would be the best alternative, assuming future NR V2X chips would integrate a LTE V2X chip as well, NR V2X not being natively background compatible.

2.4 IEEE 802.11bd (a.k.a NGV)

The IEEE 802.11bd (later referred to as DOT11BD) is an evolution of the IEEE 802.11p (a.k.a DOT11P) integrating all technology improvements available in IEEE 802.11ax (a.ka. DOT11AX) into a vehicular highly mobile context. It is naturally background compatible (e.g. a IEEE 802.11ax must be able to decode IEEE 802.11a transmissions) and has been proposed by IEEE not only as to provide one technology solution but to define a roadmap for the evolution of IEEE 802.11p technologies for future automated robotics.

2.4.1 Bit rate

One major improvement of DOT11BD over DOT11P is to integrate the higher bit rate available in DOT11AC, yet keeping the half-clock 10Mhz option required to handle Doppler and high mobility. Figure 8 provides an illustration of the different data rates, considering a single stream. The improvement should not be considered from the maximal values (86Mbps instead of 54Mbps) but from the default values. DOT11P operates at QPKS ½ by default, providing a 6Mbps data rate. Considering the DOT11BD enhancements, DOT11BD is expected to operate on 16QAM 2/3 by default, providing a data rate of 58Mbps. Accordingly, DOT11BD is expected to provide a data rate improvement of a factor of 10.

Mod	Coding rate (R)	Coded bits per subcarrier (NBPSC)	Coded bits per OFDM symbol (NCBPS)	Data bits per OFDM symbol (NDBPS)	Data rate [Mb/s] (20 MHz channel spacing) short/long GI	Minimum Sensitivity [dBm]	SINR Threshold (dB)
BPSK	1/2	1	52	26	**6.5 / 7.2**	**-82**	**5**
QPSK	1/2	2	104	52	**13.0 / 14.4**	**-79**	**10**
QPSK	3/4	2	104	78	**19.5 / 21.7**	**-77**	**13**
16-QAM	1/2	4	208	104	**26.0 / 28.9**	**-74**	**16**
16-QAM	3/4	4	208	156	**39.0 / 43.3**	**-70**	**19**
64-QAM	2/3	6	312	208	**52.0 / 57.8**	**-66**	**22**
64-QAM	3/4	6	312	234	**58.5 / 65.0**	**-65**	**25**
64-QAM	5/6	6	312	260	**65.0 / 72.2**	**-64**	**27**
256-QAM	3/4	8	416	312	**78.0 / 86.7**	**-59**	**30**

Figure 8 IEEE 802.11bd Bit Rate [source: IEEE 802.11-2016 VHT]

Moreover, this only considers a single data stream, and the data rate values can be quadruped if all data streams and Space-Time block codes could be used.

2.4.2 Time considerations

DOT11BD being an evolution from DOT11AC/AX supporting highly mobile environments, it yet keeps its CSMA-CA medium access control mechanisms. While not providing strict QoS guaranties as infrastructure operated LTE networks, DOT11BD also inherits of one of the biggest asset of CSMA-CA, a native sub-ms channel access time. Accordingly, DOT11BD is expected to support sub-ms access delay.

2.4.3 Robustness/Interferences

Inheriting from DOT11AC, DOT11BD supports beamforming, which provides a stronger protection against interferences and potential cyber-physical attacks. Moreover, DOTBD also supports a carrier aggregation and multi-channel communication natively, which provides additional protections against interferences, beside increasing capacity.

DOT11BD also supports mmWAVE communications, inheriting from DOT11AD (itself being an adaptation of DOT11AC). Strong directional beamforming provides natural protection against interferences and cyber-physical attacks. A 1Ghz ITS spectrum has been made available to ITS services, which is expected to be used by DOT11BD (and maybe also NR V2X due to the EU technology neutrality policy), as illustrated on Figure 9.

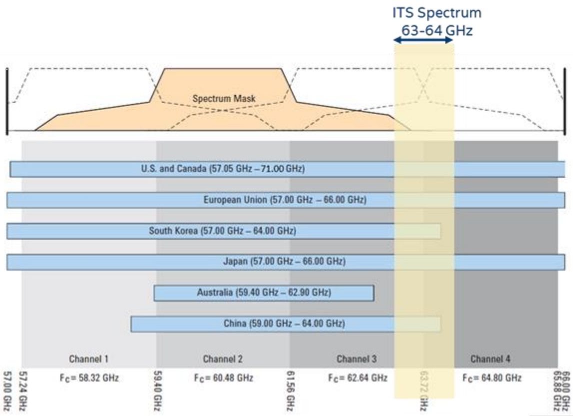


Figure 9 mmWAVE band depicting the ITS Spectrum

2.4.4 Practical considerations

IEEE 802.11BD is the answer of the WiFi industry to the 3GPP V2X roadmap vision. It provides state-of-art technologies for V2X communications, fully backward and forward compatibility (natively in WiFi technology) and is also expected to provide an increased coexistence support. The DOT11BD specification is expected to be completed by the end of 2019 with first devices being commercially available around 2025 (similar timeline as NR V2X).

One current limitation of DOT11BD remains the non-deterministic scheduler. Yet, several efforts in providing TSN over WiFi opens the door for future TSN-compatible WiFi and thus DOT11BD technologies.

2.5 WiFi

2.5.1 Bit rate

The WiFi bitrate depends on various aspects, ranging from the bandwidth, the type of PHY (legacy, HT or VHT), the number of data streams and number of antennas. Considering VHT (IEEE 802.11ac), 20Mhz and a single stream, Table 3 provides the bit rate as function for encoding rate. Considering that WiFi could sustain VHT up to 160Mhz and up to 8 streams, the maximum bit rate supported by WiFi is provided on Table 4.

As it can be seen, the maximum bit rate for a 20Mhz IEEE 802.11ac compliant WiFi system is 86.7Mbps, but this bit rate can be increased up to 6.9 Gbps considering 160Mhz and 8 stream. Yet these values have to be understood as occurring under the optimal conditions, meaning static topology (no doppler) with direct line of sight and at close range, three conditions that are hardly met in vehicular or rail conditions.

2.5.2 Time considerations

The time consideration in WiFi should be split in two parts. First the access time (the time to send a packet on the wireless channel) and the management time (the time the WiFi requires to set up the WiFi network). For the channel access time, WiFi being a CSMA-CA access technology, the delay cannot be guaranteed. We analyse it from a best/worst case situation. The access delay depends on three parameters:

- AIFN: an Arbitrary Interframe Spacing Number (AIFN) is a fixed time that any WiFi station must wait before decreasing the backoff counter. This value depends on the traffic class

- CW: a Contention Window (CW) is a random time corresponding to a contention window set to avoid collisions.
- Slot time: the minimum unitary time in IEEE 802.11 systems

Together, the addition of the AIFN and the CW multiplied by the Slot time provides a minimum contention delay, which must be respected by WiFi stations before trying to send anything on the channel. Please note that even the 'max' values only represents the maximum contention value, not the maximum access delay, as a WiFi station freezes its contention timer as long as the channel is occupied by other transmissions. According, under strong channel occupation, the WiFi channel access delay may increase significantly and be unbounded.

Nevertheless, what we can see is that the contention delay is largely sub-ms range (below 1 ms in most cases), and even considering the potential contention timer freeze, a typical WiFi channel access delay ranges between 1ms to 20ms, although being unbounded.

On top of this, the WiFi management delay is a bit trickier. A WiFi node may not communicate without having joined a Basic Service Set (BSS) and being authenticated by the AP (see Figure 10 and Figure 11).

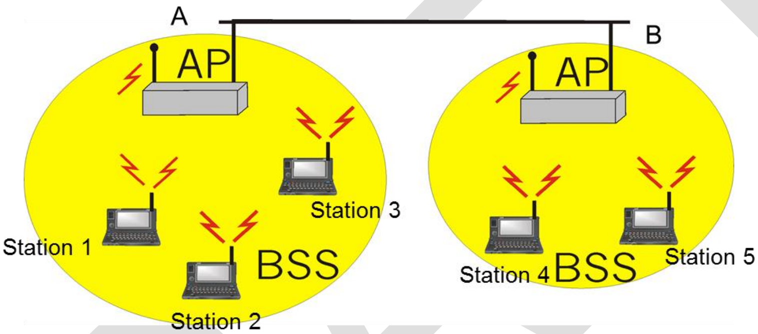


Figure 10 WiFi BSS concept

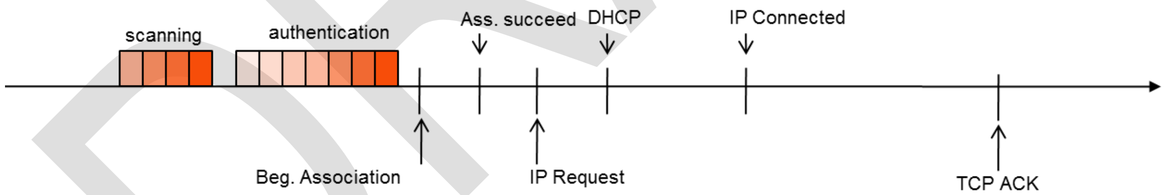


Figure 11 WiFi BSS Association Steps

This process is cumbersome and takes time in the current IEEE 802.11-2016 specification[1]. Table 2 provides association delay for WiFi systems, and even if ignoring IP, and even assuming the scanning phase is not required as all WiFi systems know the right channel to communicate, joining a BSS requires at least 560ms delay, significantly larger than a WiFi packet.

This was the reason the IEEE 802.11 created a vehicular amendment (DOT11P), later known as 'Outside the Context of a BSS' (OCB), which basically means that a WiFi node may communicate without a BSS (Basic Service Set). Unfortunately, the OCB mode is restricted to the vehicular domain and cannot be used by other WiFi systems.

[1] The IEEE is currently working on amendments for fast BSS joining process.

Table 2 WiFi association delay[2]

Mean scan duration	750 [ms]
Mean association duration	560 [ms]
Mean DHCP IP Acquisition	1830 [ms]
Mean time before first TCP ACK	4900 [ms]
Total	8040 [ms]

2.5.3 Robustness/Interferences

WiFi operate in ISM bands, which means that it shares its spectrum with potentially unlimited other WiFi systems or even different technologies. Accordingly, WiFi is severely subject to interferences and performance degradation. In order to mitigate this, the DOT11AC has been extended to support beamforming in the mmWAVE band under the name DOT11AD.

2.5.4 Practical considerations

WiFi is a COTS technology that reaches both bit rate and delay requirements for the WLTB. However, it is subject to heavy and unbounded interferences in the ISM band. One option for WLTB RD would be to use WiFi in dedicated radio bands. Another option would be to operate the WIFI with beamforming in the mmWAVE band.

Beamforming in WiFi is a robust strategy to mitigate interferences but also at a cost: the position of the MN (Mobile Nodes) must be discovered/known to adjust the beam. Accordingly, directing the beams in the correct direction adds delay and performs better under static or mutually-static mobility. Yet, in rail environments, it is highly unlikely that the position between AP and MN will change rapidly so operating WiFi in the mmWAVE (>20GHz) bands is a promising strategy for WLTB RD. Please note that DOT11BD being an extension of DOT11AC, it also operates on the mmWAVE, thus could then be acting for TCMS domain, whereas the DOT11AD would act for the OMTS domain.

[2] Source: Bychkovsky et al. , “A Measurement Study of Vehicular Internet Access Using In Situ WiFi Networks, ACM Mobicom, 2006

Table 3 WiFi VHT bit rate for 20Mhz single stream

Modulation	Coding rate (R)	Coded bits per subcarrier (NBPSC)	Coded bits per OFDM symbol (NCBPS)	Data bits per OFDM symbol (NDBPS)	Data rate [Mb/s] (800ns GI)	Data rate [Mb/s] (400ns GI)	SINR Threshold [dB]
BPSK	1/2	1	52	26	**6.5**	**7.2**	**5**
QPSK	1/2	2	104	52	**13**	**14.4**	**10**
QPSK	3/4	2	104	78	**19.5**	**21.7**	**13**
16-QAM	1/2	4	208	104	**26**	**28.9**	**16**
16-QAM	3/4	4	208	156	**39**	**43.3**	**19**
64-QAM	2/3	6	312	208	**52**	**57.8**	**22**
64-QAM	3/4	6	312	234	**58.5**	**65**	**25**
64-QAM	5/6	6	312	260	**65**	**72.2**	**27**
256-QAM	3/6	8	416	312	**78**	**86.7**	**30**

Table 4 WiFi VHT for 160Mhz 8 streams

Modulation	Coding rate (R)	Coded bits per subcarrier (NBPSC)	Coded bits per OFDM symbol (NCBPS)	Data bits per OFDM symbol (NDBPS)	Data rate [Mb/s] (800ns GI)	Data rate [Mb/s] (400ns GI)	SINR Threshold [dB]
BPSK	1/2	1	3744	1872	**468**	**520**	**5**
QPSK	1/2	2	7488	3744	**936**	**1040**	**10**
QPSK	3/4	2	7488	5616	**1404**	**1560**	**13**
16-QAM	1/2	4	14976	7488	**1872**	**2080**	**16**
16-QAM	3/4	4	14976	11232	**2808**	**3120**	**19**
64-QAM	2/3	6	22464	14976	**3744**	**4160**	**22**
64-QAM	3/4	6	22464	16848	**4212**	**4680**	**25**
64-QAM	5/6	6	22464	18720	**4680**	**5200**	**27**
256-QAM	3/6	8	29952	22464	**5626**	**6240**	**30**
256-QAM	5/6	8	29952	24960	**6240**	**2933.3**	**32**

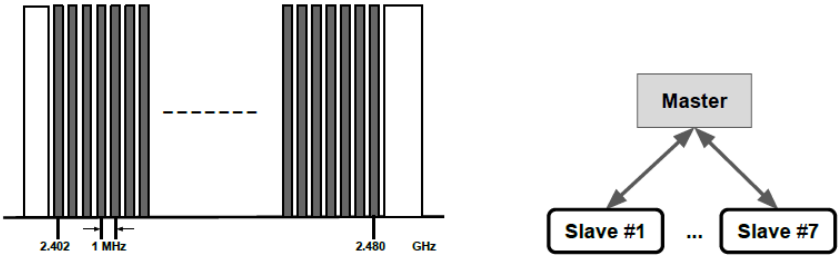
Table 5 WiFi contention delay

AC	Slot time [µs]	Cwmin	CWmax	AIFN	Contention Delay Min [ms]	Contention Access Delay max [ms]
AC_BK	9	31	1023	7	0.342	9.270
AC_BE	9	31	1023	3	0.306	9.234
AC_VI	9	15	31	2	0.153	0.297
AC_VO	9	7	15	2	0.081	0.153

2.6 BLE

The Bluetooth (BT) radio technology is one of the most popular and widely used Personal Area Network (PAN) technology. Originally invented by Ericsson in 1994, it is nowadays found in most of the mobile devices, including vehicles. As WiFi, BT operate on the 2400-2485.5Mhz ISM band, but unlike WiFi, which takes a large 20Mhz band for its operations, BT relies on 79 narrow bands of 1Mhz (see Figure 12(a)) and performs frequency hopping (1600 hops per second via a predefined sequence) in order to mitigate interferences between BT but also against WiFi.

From a management perspective, BT relies on a Master-Slaves architecture, where one BT device operates as Master and multiple BT devices will be connected and controlled by the Master (see Figure 12(b)). Accordingly, an efficient coordination is maintained for the transmissions from multiple BTs. However, the limitation comes from the discovery and organization time that would be required to form this topology.



(a) Hopping Channels. (b) Architecture.

Figure 12 Bluetooth General Operations [source: W. Bronzi [11]]

Bluetooth Low Energy (BT) has been introduced in 2006 also by Nokia with the objective to reduce the energy consumptions of the BT devices, yet keeping the bit rate. Compared to BT, the management functions of BLE has been simplified. Notably the lengthy (and energy demanding) pairing procedure between Master and Slaves has been removed. In order for BLE to associate with other BLE devices, new "advertising channels" have been proposed. Also BLE has 2MHz-wide channels compared to the 1Mhz of BT, only 40 narrow bands remaining. BLE still operates in ISM bands also relying on Frequency Hopping (FH) in order to mitigate interferences. Figure 13 depicts the differences between BT and BLE technologies.

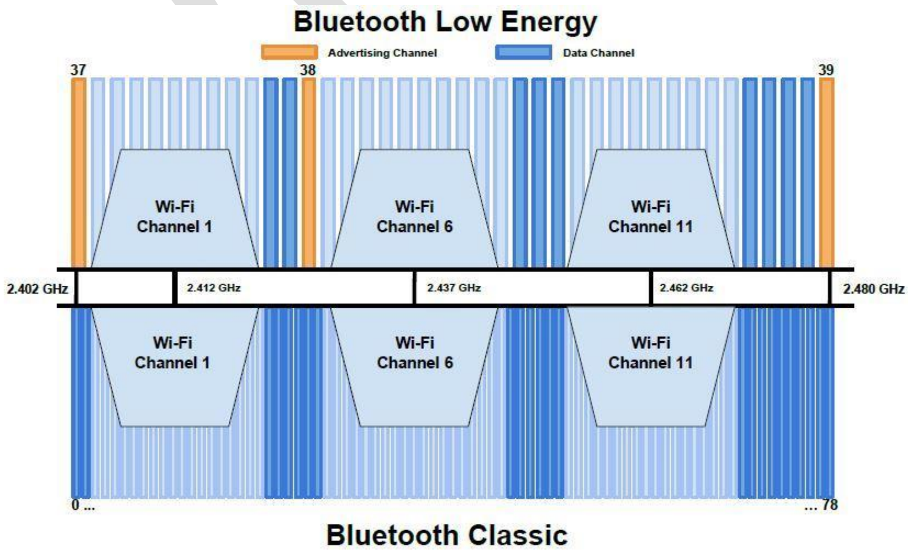


Figure 13 BT versus BLE operations [source: W. Bronzi [11]]

2.6.1 Bit rate (optimal range)

BT operates as FH relying on a Gaussian Frequency Shift Keying (GFSK), which allows smoother transitions between the different pulses and avoiding out-of-band interferences. The original bit rate was 3Mbps over a 100m rage.

BLE has been built on top of BT version 4, which has several differences. Whereas its maximum range remains 100m, the bit rate has been reduced to 2Mbps.

2.6.2 Time considerations

BT original latency (mostly from the pairing procedure) is 100ms. BLE inheriting from BT version 4 advertisement vs. pairing mechanisms manages to reduce it to 6ms.

2.6.3 Robustness/Interferences

BLE as BT are robust technologies against interferences, as they have been purposely designed to this objective. The FH strategy over a 2Mhz narrow band avoids interfering with other BT/BLE technologies unless using the same permutation scheme. Second, FH avoids interfering with wide(r) band technologies (e.g. WiFi) as the narrow-band energy perceived by any wideband radio is insignificant.

2.6.4 Practical considerations

BLE has been well investigated in the automotive domain and has been shown to be quite useful and efficient for critical and non-critical transmissions. In [11], it has also been studied for Mesh/Multi-hop relaying with success.

Although non negligible, the 6ms delay is compensated by an almost error-free transmissions and as such supports time-sensitive communications. The limitations are first to share the different FH permutation codes and discover services in a dynamic way, second the 2Mbps bit rate and third the 50m range limit.

2.7 VLC Visible Light Communication

Visible Light Communication (VLC) is an optimal wireless communication system, where the signal is produced by a light emitting diode (LED) emitting in the visible light spectrum over a potentially 300 THz wide spectrum. Data is encoded and modulated according to a LED Intensity Modulation (IM). The most known encoding scheme is called On-Off Keying (OOK) modulation, where ‘1’ is modulated with the LED at maximum intensity and a ‘0’ with the LED at minimum intensity. The bit rate is therefore controlled by how fast IM can be performed by the LED. Although highly directional, VLC may still be subject to interferences by LED signals interfering at the receiver if multiple VLC transmitters would be too close and the LEDs not sufficiently directional.

Very attractive in the Automotive Industry due to the large presence of LEDs in head and tail lights, the performance of VLC strongly depends on the quality of the LEDs, but showed to be very promising complementary wireless technology.

2.7.1 Bit rate

VLC bit rate strongly depends on the quality of the LEDs and the modulation/ coding scheme. If early work relying on OOK with COTS LEDs could reach 2Mbps, the most recent work, replacing the OOK with advanced modulation such as OFDM and high rate LEDs reached up to 60Mbps [12]. VLC communication range is yet limited to 1-2m. Although the range clearly would not match WLTB range requirements, the bit rate easily does.

2.7.2 Time considerations

With virtually immediate access to the channel, delay in VLC is almost fully defined from the time the LED requires to emit a pulse and the coding overhead (e.g. transmitting 110011 instead of 101). [12] showed that COTS LEDs could reach a delay below 20ms, which should match most of the WLTB delay requirements.

2.7.3 Robustness/Interferences

One strong asset from VLC technologies is its robustness to interferences. Although being sensitive to ambient lights, considering a directional electro-diodes at the receiver, interferences would basically mean having a VLC interferer in between both Tx and Rx or immediately nearby (see Figure 14). In a WLTB context, and considering 1m optimal communication range, such situation is highly unlikely as illustrated in [12] (less than 6.5% interference in a highway platooning scenario, mostly resembling that of a WLTB in Virtual Coupling).

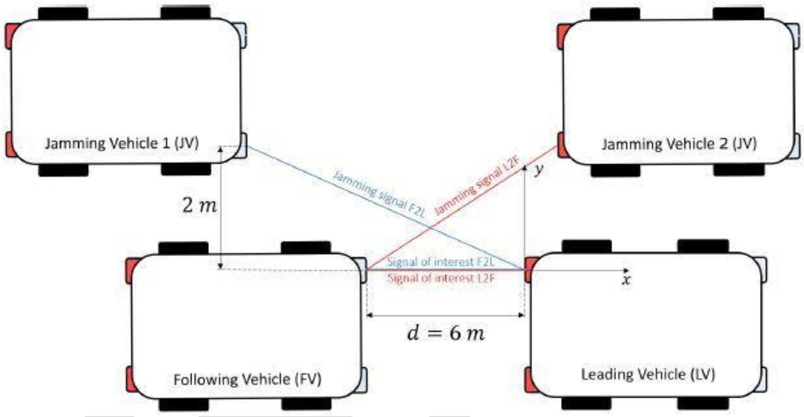


Figure 14 VLC potential interfering configuration for WLTB [source: [12]]

2.7.4 Practical considerations

VLC has been subject to an increasing interest over the last few years, in particular in the automotive industry. First as LEDs are widely available, but also as modulation can be optimized separately from the LED technology (although a joint design would be more efficient). Nevertheless, although limited in range, VLC is considered as a very promising complementary technology to RF systems, first as a very large band is available (up to 300THz), second as it does not interfere with RF signals, third as it can integrate modern modulations reaching up to 60Mbps bit rate at very low delay, and finally it is strongly directional thus difficult to interfere with.

Accordingly, considering the potential presence of LEDs in front/tail lights in each consists, VLC could be considered as a solid redundant wireless technology for the WLTB to RF technologies. In [12] Bechaderge suggested to jointly use RF and VLC for automotive platooning.

For example, would the RF-based WLTB be based on a Mesh architecture, a redundant VLC-WLTB could be based on a linear architecture. This option could be investigated by S4R2 if the CFM considers it as an option.

2.8 Frequency Bands for Railway

One key challenge when designing a new radio equipment is to identify available frequency bands. Considering the railway industry, this task is particularly challenging as it does not correspond to an operator but requires exclusive access and is highly mobile, thus requires EU-wide reserved spectra.

After a decade of development, the Railway industry proposed a dedicated GSM-R technology in 2000 operating on dedicated bands in 900Mhz and 1800Mhz. Through CEPT, GSM-R in Europe has the following frequency ranges:

- Uplink: 876MHz-880MHz (4Mhz)
- Downlink: 930MHz-934MHz (4Mhz)

With new applications in the ETCS and NG-TCMS, the IUC is currently considering its replacement by a 5G technology.

Figure 15 depicts the spectrum to be allocated for future 5G systems in the EU, US and China. For the EU, three major bands are targeted: 703-788MHz, 3.4-3.8GHz and 24-25GHz. At the time of writing, it is not clear where would be located the spectrum for the upcoming NR V2X (5G Rel.16).

Additionally, the 5G ‘High Band’ for mmWave communication is tailored for commercial 5G traffic. The ITU further allocated 1GHz band in the 63-64GHz band as depicted on Figure 9. It is yet highly likely that this band will be shared between NR V2X and DOT11BD.

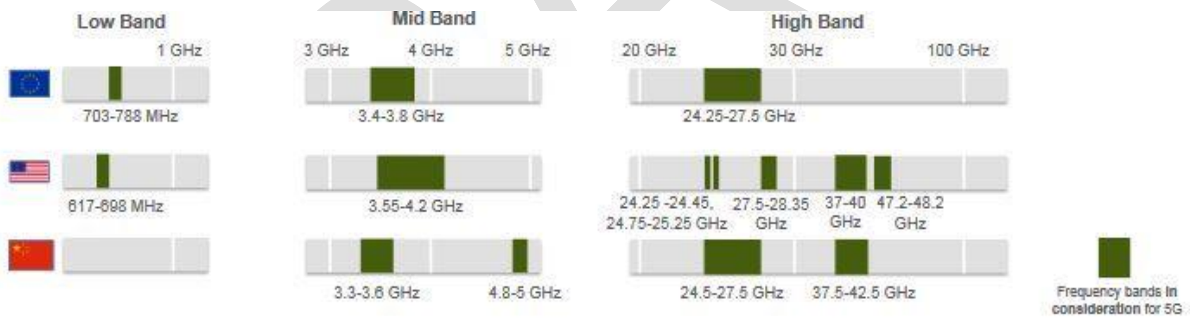


Figure 15 Frequency bands planned for 5G [source: 5GCAR]

Considering the LTE-V2X technology, 3GPP assigned the ITS spectrum for the Sidelink (SL) communication. Yet, the integration of LTE V2X with the legacy LTE requires synchronization in the LTE commercial band. Accordingly, LTE V2X can be handled as follows:

- **V2V (mode 4):** ITS frequency band as depicted on Figure 16.
- **V2V (mode 3):** ITS frequency band for SL and 3GPP bands illustrated on Table 6.
- **V2N:** LTE over the Uu interface is handled according to the 3GPP bands illustrated on Table 6.

As it can be observed, the V2N and V2V mode 3 operations require LTE commercial bands on the UL (LTE Uu interface), which needs to be integrated to design requirements for WLTB, both in terms of coverage and cost.

Table 6 LTE Uu Frequency Bands (for LTE-V2X mode 3)

3GPP Band Number	Uplink (MHz)	Downlink (MHz)	Duplex Mode	Combined with ITS Band
3	1710-1785	1805-1880	FDD	Yes
7	2500-2570	2620-2690	FDD	Yes
8	880-915	925-950	FDD	Yes
20	832-862	791-821	FDD	Yes

On the V2V (mode 4 and mode 3 SL), the ITS Safety bands are currently the only ones allocated European-wide at the time of writing. The 5.855-5.885GHz ITS bands are not expected to be available for WLTB communication (except maybe for the OTMS plane), considering the non-safety type assigned to this band. Discussions are ongoing to allocate the 'future ITS' upper 5.905-5.925GHz upper bands but at the time of writing, it is restricted to urban rail and not to mainline Railways. Summarizing:

- **ITS non-safety band 5.855-5.885GHz**: TCMS not allowed, OTMS possible
- **ITS safety band 5.855-5.905GHz**: restricted to road vehicles (car, bus,…)
- **ITS safety band 5.905-5.925GHz**: restricted to urban rail (trams, subways)

As it can be observed, the ITS spectrum is not openly available to the rail industry for its WLTB and Wireless TCMS communications. At the time of writing, access to the upper ITS safety band might still be possible subject to strong lobbying. Nevertheless, the weak point of using the ITS bands for Wireless TCMS communications is the potential interferences with other ITS actors and potential enforced co-existence mechanisms. An alternative would be to rely on the reuse of the GSM-R band.

Figure 16 ITS Band at 5.9GHz in EU for both LTE V2X and ITS-G5 [source: 5GCAR]

2.9 Discussions

Various technologies exist for the WLTB radio and is depicted on Table 7, along with the technical requirements for the WLTB. As it can be observed, none of the current technologies fulfil the requirements for the WLTB RD. The future technologies (DOT11BD and NR V2X) are promising as they reach most of the requirements (except Mesh).

According to Table 7, the WiFi technology (ITS-G5 and DOT11BD) do not provide better requirement support compared to LTE-V2X and NR V2X. Accordingly, considering the technologies selected by the rail industry for Train2Ground, FRMCS and inheriting from GSM-R, the cellular technology is selected for WLTB RD, building from LTE V2X and targeting a smooth transition to NR V2X. The VLC technology could be considered as a complementary strategy over a redundant WLTB architecture (mesh and linear), would the CFM project see this as a valid option.

Considering LTE Prose (D2D/V2X),

Table 8 compares the requirements for WLTB RD and LTE D2D, V2X and NR V2X. As it can also be seen, only NR V2X actually supports all requirements (except Mesh), while each D2D and V2X only support complementary requirements (e.g. LTE D2D supports service discovery/group com, whereas V2X does not).

Table 7 Wireless Technology Comparison for the WLTB radio

		WIRELESS TECHNOLOGIES						
REQUIREMENTS		*LTE-V2X [2,3]*	*ITS-G5 [1]*	*Wi-Fi [4,5,6, 7]*	*VLC [8,9,12]*	*BLE [10,11]*	*DOT11BD*	*NR V2X*
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	*estimation*: (1) <2-3Gbps (2) <20Gbps	*estimation*: (1) <2-3Gbps (2) <20Gbps
Max. Latency	16-500ms	50-100ms	1-20ms	(1) 1 - 20ms (2) 5-250ms	20-40ms	50ms-1000ms	*estimation*: (1) 1 - 20ms (2) 5-250ms	*estimation*: (1) 1 - 20ms (2) unknown
Medium Access	Deterministic	Mode 3: Deterministic Mode 4 Non-Deterministic;	Non-Deterministic	Non-Deterministic	Non-Deterministic	Deterministic	Non-Deterministic	Non-Deterministic (mode 2(b)) & Deterministic (mode 2(d))
Communication Range	up to 820m	300m-1000m	300m-1000m	(1) > 200m (2) < 2m	5m-20m	50m-200m	*estimation:* <1000m	*estimation:* <1000m
Group Communication	Multicast/Group	-	-	(2) DOT11y	-	Clustering	Multicast/groupcast	Multicast/groupcast
Mesh Capabilities	up to 32 nodes	-	Geonet/1609.3	DOT11s	-	inter-cluster	Geonet/1609.3	-
Freq. reuse	1 / car	SL-subpools (2-3)	-	ISM, mmWave	Directional	ISM	Carrier aggregation (Mx10Mhz)	SL-subpools (2-3)
Protect. against interferences	-	-	-	(1) DSSS+Freq Hopping (2) BeamForming	Beam Forming	Freq. Hopping	BeamForming	BeamForming

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.

Considering the fact that there is no clear information of chipset availability for LTE D2D (public safety) and the NR V2X are not expected to be available commercially before 2025, the following strategy will be followed:

- Demonstrator: WLTB RD prototype will be based on LTE V2X with an additional overlay module to handle the missing features (service discovery, group communication and mesh networking)
- Research: NR V2X will be investigated and adapted to the need of the WLTB RD for the RF aspect on a Mesh architecture. Potentially, VLC could be investigated for WLTB RD on a linear architecture.

Table 8 Comparison between LTE Prose (D2D,V2X) and NR V2X

Requirements	LTE D2D	LTE V2X	NR eV2X
Service Discovery	Yes	No	Yes
Group Com.	Yes	No	Yes
Multicast/Broadcast	Uni/broadcast	Broadcast	Multicast/Groupcast
Sub-carrier spacing	15kHz	15kHz	15,30,60, 120kHz
Reliability	No	No	HARQ/NACK
Spectrum access	700Mhz (PS), Commercial	5.9GHz	6GHz & 60GHz*
Scheduling	not specified	Mode 3: eNB scheduling Mode 4: LBT, SPS	Mode 1: gNb scheduling Mode 2 : flex. sub-modes
Scheduling interval	sub-frame (1ms)	sub-frame (1ms)	Mini-slots (0.125ms)
Mesh	higher layer	higher layer	higher layer
Chipset availability	not known	2020	>2025

*NR V2X frequency bands are still under discussion at that time

Chapter 3 Networking Technologies State-of-Art

The future WLTB node will not only need to provide wireless access but also means to organize multiple consists in a mesh topology as depicted on Figure 17. Accordingly, the future WLTB node will need to integrate multi-hop wireless networking technologies. Similarly to the Access Technologies, the wireless networking technologies will need to be self-organizing. Accordingly, this chapter focuses on the state-of-art ad-hoc networking technologies, notably used for Mobile Ad Hoc Networks (MANET).

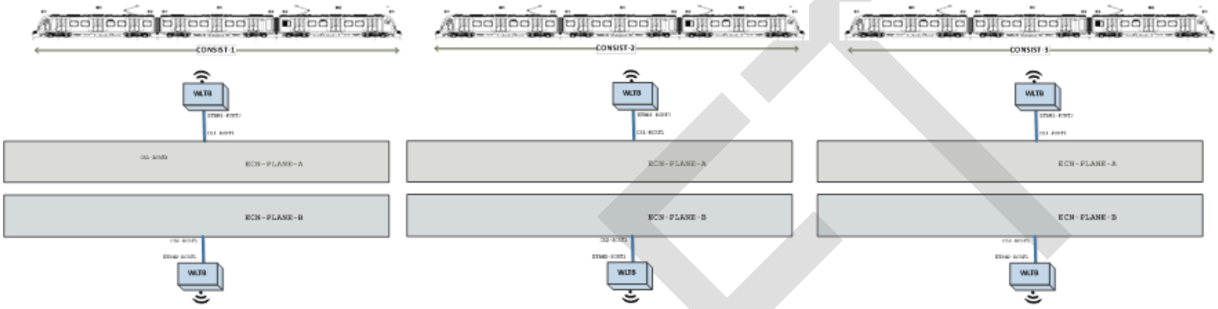


Figure 17 WLTB Mesh Architecture [13,14]

3.1 State-full Ad-Hoc Routing

Stateful routing/networking is an approach, where each router maintain the state of the network (reachability of each link). Accordingly, if the topology or the network conditions change, the routers have to recompute the state of the impacted links. Two different strategies exists in stateful routing: proactive and reactive. Proactive routing computes the state of all potential destination in the network, whereas reactive routing computes the state of only active links.

3.1.1 Proactive: Optimized Link State Routing (OLSR)

The OLSR protocol is the most known and used proactive protocol, standardized by the IETF [RFC]. Several implementations may be found in the community. OLSR operates in two steps: first a two-hops topology discovery protocol triggered by each node sending a MPR (MultiPoint Relay) message detects the most optimal relay reaching all two hops neighbors. Second, a multi-hop link state mechanism performed by each node sending a Topology Control (TC) message allows to discover the most optimal multi-hop route to the sender. The MPR phase allows to disseminate the TC messages minimizing the overhead. At convergence, each OSLR router has an entry indicating the next hop to reach any nodes in the network, as well as the number of hops to reach them. Figure 18 depicts the OLSR protocol.

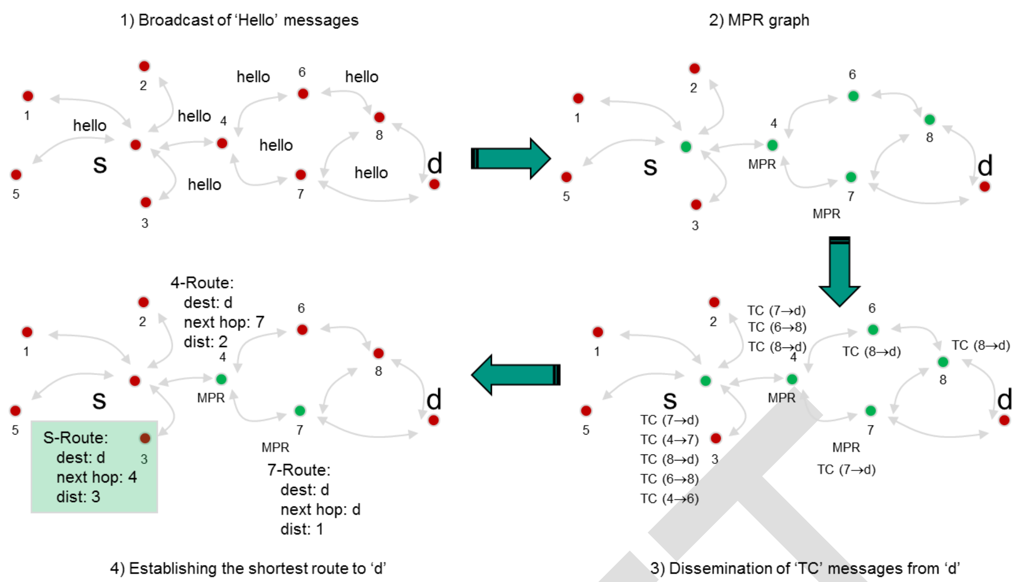


Figure 18 OLSR Protocol Description

3.1.2 Proactive: Better Approach To Mobile Ad-hoc Networking (B.A.T.M.A.N.)

B.A.T.M.A.N[3] is another proactive stateful ad-hoc network protocol, which extend many concepts from OLSR. B.A.T.M.A.N. however differs from OLSR in one major direction: whereas OLSR needs to compute link state between all nodes in the network to select the best relay, B.A.T.M.A.N. simplifies this requirements by only keeping state information over 1-hop only. This brings significant advantage over OLSR for city-wide mesh networks.

The initial implementations of B.A.T.M.A.N. where on IP, but since B.A.T.M.A.N. III, a Link layer (L2) version has been proposed.

3.1.3 Reactive: Advanced On-Demand Distance Vector (AODV)

The AODV protocol is also a well-known multi-hop routing protocol standardized by the IETF [RFC]. Unlike OLSR, AODV only build multi-hop routes on-demand, minimizing the overhead to maintain the overall state at the cost of a route establishment delay.

AODV operates in two phases: first, a Route Request (RReq) message is sent by a node to find a destination node. Being sent in broadcast, the RReq message is relayed by each node until an entry to the destination is found in its router. It then moves to the second phase, where that node replies with a Route Reply (RRep) in Unicast following the exact path followed by the bread crumb left by the RReq. The route is established when the RRep reaches the initial node, which then keeps the selected relay to reach its destination in its router, as well as the number of hops (as link metric). Figure 19 shows the different steps in the AODV protocol.

[3] OpenMESH: https://www.open-mesh.org/projects/open-mesh/wiki/BATMANConcept

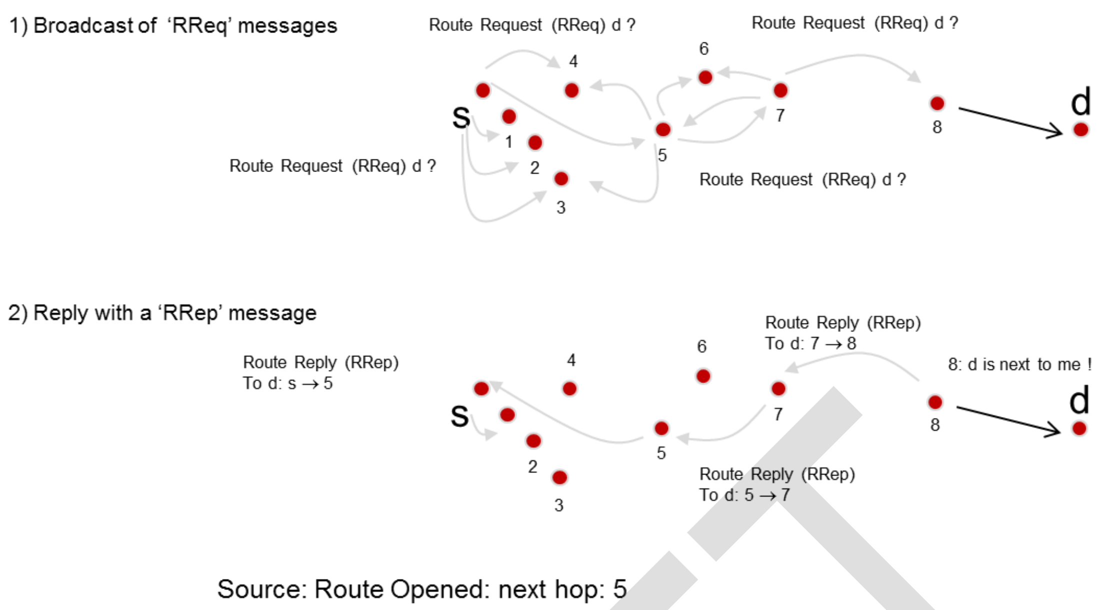


Figure 19 AODV Protocol Description

3.1.4 Hybrid Wireless Mesh Protocol (DOTs MESH)

The Hybrid IEEE 802.11s COTS mesh WiFi is an amendment to WiFi, where WiFi AP/MN have the capabilities to provide L2 multi-hop networking between each other.

One Mesh standardized protocol is the OLSR protocol previously described, yet adapted to handle MAC addresses instead of IP addresses and operating on a wireless L2 link.

Whereas the mesh technology has been well tested between COTS DOT11s APs and MNs, adapting the Mesh technology to WiFi operating Outside the Context of a BSS (OCB mode) has not been evaluated so far.

Traditionally, a Mesh approach between MN without previous association is found in sensor and vehicular networks referred as 'ad-hoc' WiFi networking, which is not a baseline WiFi product and require unconventional modification of the WiFi code. But the OpenMESH initiative[4] provide resources to build a WiFi DOT11s based MESH network.

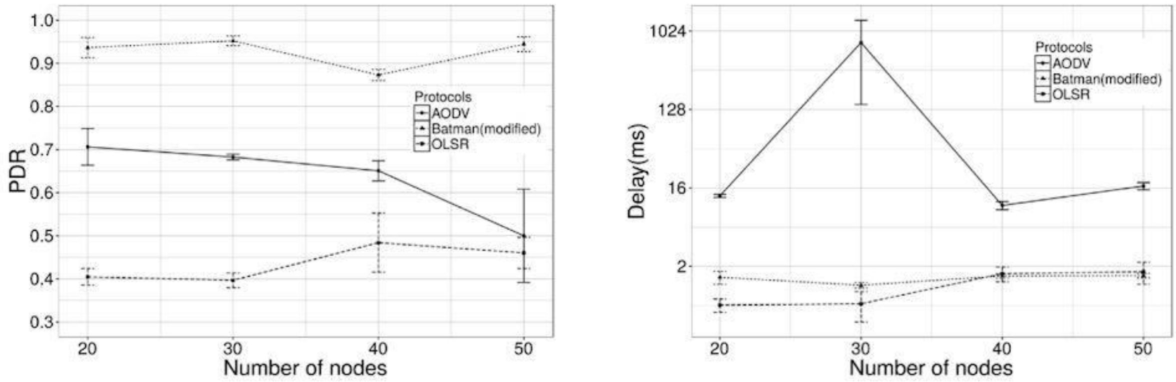
3.1.5 Comparison and Discussion

Considering a Mesh architecture for the WLTB as well as a strict restriction to provide Mesh functionalities at Link Level (L2), most of the Mesh technologies do not fulfil the requirements. Considering that a WLTB will be composed of a rather stable set of consists and that delay is critical, a proactive Mesh technology is preferred.

Figure 20and Figure 21 provide a comparison between the performances of AODV, OLSR and B.A.T.M.A.N. As it can be observed, considering B.A.T.M.A.N. V, it exceeds the performance of both OLSR and AODV. On these figures, we can also see the delay difference between proactive and reactive strategies, where OLSR provides significantly larger delays compared to AODV, but where B.A.T.M.A.N. almost matched AODV.

From a stateful perspective, B.A.T.M.A.N. is therefore considered as the most adapted MESH technology to the WLTB.

[4] OpenMESH: https://www.open-mesh.org/projects/open-mesh/wiki/BATMANConcept



a) Average packet delivery rate b) Average end-to-end delay

Figure 20 Performance Comparison Between BATMAN, OLSR and AODV [source: Sébastien BINDEL, Benoit HILT and Serge CHAUMETTE, F-ETX: A Metric Designed for Vehicular Networks]

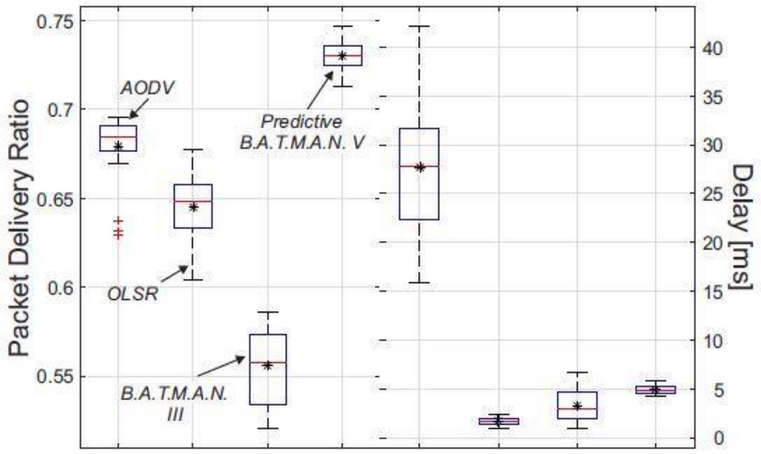


Figure 21 Performance Comparison between AODV, OLSR, and B.A.T.M.A.N. in vehicular environment [source: Benjamin Sliwa, Stefan Falten and Christian Wietfeld "Performance Evaluation and Optimization of B.A.T.M.A.N. V Routing for Aerial and Ground-based Mobile Ad-hoc Networks", IEEE VTC Spring 2019]

3.2 Stateless Ad-Hoc Routing

Unlike Stateful routing, Stateless routing does not keep any state information about the topology of the network. The major benefit from it is that it fits more to highly mobile topologies, where keeping and updating states would consume a significant amount of overhead. On the downside of stateless routing mechanisms, link metrics are inexistent and a route is determined on the fly.

3.2.1 Greedy Perimeter Stateless Routing (GPSR)

GPRS has been the first stateless routing protocol developed for highly mobile environment typically found in vehicular networks during the German FleetNet project in 2003[5]. Its principle is rather simple and operates in two phases, usually provided by two different protocols:

[5] FleetNet: https://uk.nec.com/en_GB/emea/about/neclab_eu/projects/fleetnet.html

- **Target location:** The first phase is to determine the GPS location of the target. This step usually requires to query a location server providing such information.
- **Greedy Forwarding:** A packet is then sent in broadcast with the indication of the GPS location of the destination. The neighboring node with the best geographic progress towards the destination will be selected as relay. In situation where the packet reaches a local maximum, a recovery phase is initiated to circumvent the local maximum and reach a node with a better progress.

Figure 22 illustrates the behaviour of the GPSR protocol. Whereas shown as being extremely efficient in vehicular environment, it is also problematic for Unicast messages, as an ACK would need to also follow a similar greedy progress, with no delay or reliability guarantee. GPSR is therefore more appropriate to broadcast traffic.

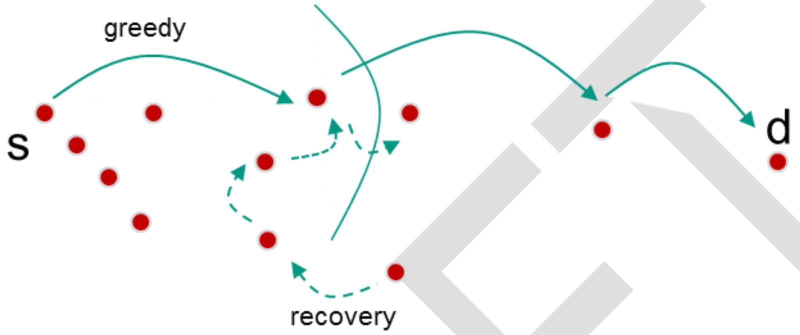


Figure 22 GPSR Protocol Description

3.2.2 ETSI Geographic Routing

The ETSI, from input from the CAR 2 CAR Communication Consortium, integrated a Stateless Geographic Routing within its Geonet stack, as described in EN 302 636-4-1. It combines two modes: greedy forwarding to explicitly select a forwarding node, but also involves a backup strategy called contention-based routing, in case the selected node would not have received the packet. The ETSI Geographic Routing is currently mostly used considering a target destination area, rather than a given node.

The Greedy Forwarding (Figure 23) allows senders to select the best relay according to the progress toward a target destination area. The advantage is a fast relay strategy, while the drawback is a potential packet loss.

The Contention-based routing strategy (Figure 24) on the other hand allows any node to relay a packet, but to mitigate a broadcast storm, each node will relay if and only if no other node has done it already once a given timer expires, which is directly proportional to the progress distance. Once a node relays a packet, all other nodes will cancel the relay. The advantage of this strategy is the multiple contingency plan (many nodes may relay the same packet), while the drawback is the delay involved in the timer strategy.

The ETSI allows both modes, although in practice, only the contention-based routing is used.

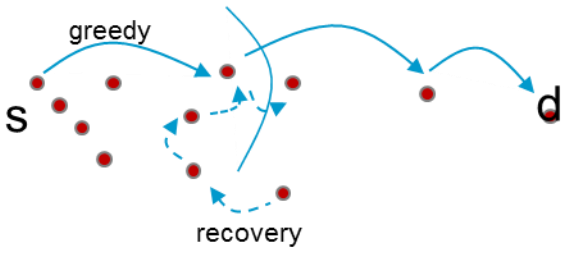


Figure 23 Greedy Forwarding

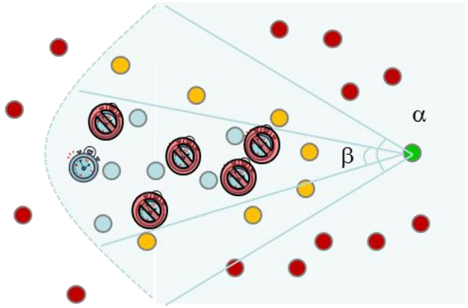


Figure 24 Contention-based Routing

3.3 Discussion

In this section, we presented various ad-hoc networking protocols, which have been developed for mobile ad-hoc networks and adapted to vehicular environment. Whereas the stateful routing approaches provide routing tables and as such tighter control on how to reach a specific destination, they also suffer from a large overhead for maintaining these routing tables in a highly dynamic environment. Stateless routing on the other hand do not maintain any routing tables and as such do not waste wireless resources for management.

However, stateless routing is opportunistically determined with unbounded delay and mostly will involve different paths between different packets, in particular acknowledgements. Such limitations have been largely ignored as stateless routing have usually been studied either for broadcast communications or in non-safety contexts. Moreover, it requires GNSS information, which cannot be fully guaranteed.

In S4R2 context, it is not expected to have highly dynamic 'mutual' mobility, but it requires control in delay and ack/nack paths. Accordingly, a stateful approach is more adapted. Within the statefull strategies, OLSR and BATMAN are most optimal candidates. Considering the superior performance of B.A.T.M.A.N. and its availability in L2, S4R2 will adapt B.A.T.M.A.N. for its WLTB Mesh routing.

Chapter 4 WLTB Demonstrator Description

In this chapter, we describe the architecture design for the WLTB radio device.

4.1 Hardware Schema

The WLTB radio is based on the OpenAirInterface™ SDR platform. This means that all LTE-V2X rel.14 procedures are available in software. However, a radio-front end and power amplifiers are required to do the D/A operations and transmit the actual signals. Moreover, a GPSDO (GPS Disciplined Oscillator) is required to synchronize the radio front-end.

Accordingly, the WLTB radio is designed as depicted on Figure 25, including the TCMS and OMTS domains.

Considering the TCMS domain, as input/output, it has an Ethernet port, three antennas for the two Radio Front-ends and the GNSS device. The Ethernet port allows the WLTB radio to be connected to ETBNs, whereas the front-end antennas allows the WLTB radio to be connected to other WLTBN or to a LTE eNB and the Internet.

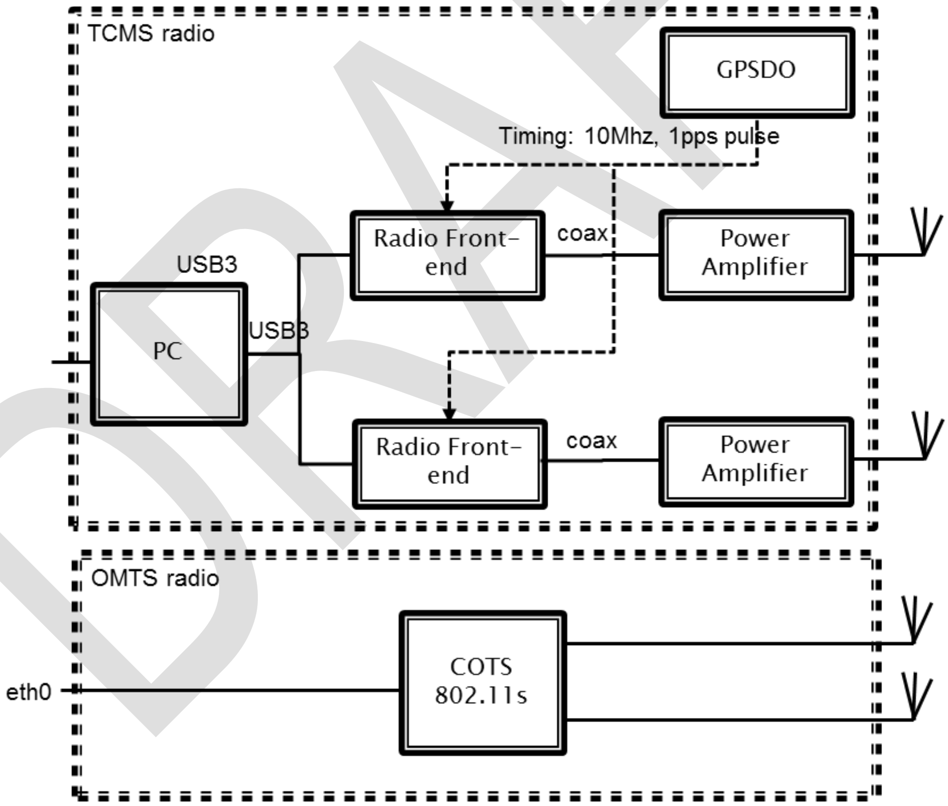


Figure 25 WLTB Radio Architecture, including TCMS and OMTS Radios

In more details, the WLTB radio is composed of the following components:

- A PC (Computer) – the OAI software and LTE ProSe procedures are being run there. Moreover, the PC will be configured to operate as a bridge for the ETB via the ETH0 interface. It will need to handle two radio-front-ends, one for the sidelink (mode 1/2/3/4) and one for the uplink/downlink communications (mode 1/3).
- Radio Front-end – Operating the D/A and A/D procedures to modulate the signal to the target frequency range. It requires an external disciplined oscillator to synchronize the front-end internal clock.
- Power Amplifier – the radio front-end emits signals around 0dBm. In order to reach the target transmission range, a power amplifier will be required to increase the output power to ~25dBm.
- GPSDO device – clock synchronization will be performed through a disciplined oscillator. It is designed to support GPS, but also designed to provide the required synchronization in the absence of GPS signal.

Considering the OMTS domain, a COTS DOT11s MESH technology will be used. The reason for this choice comes from the ITS frequency access restrictions, where OMTS signals would not be allowed. Considering that OMTS data is less critical and could be transmitted over an ISM band, COTS DOT11s has been selected for the demonstrator. However, this does not preclude any other wireless and cellular radio technologies to be investigated as replacement by the S4R2 project.

4.2 Hardware Selection

After a careful review of the requirements and the hardware capabilities, the selected hardware is described on Table 9.

Table 9 WLTB hardware selection

Components	Hardware	Link	Notes	Tested
Common Hardware				
PC	Gigabyte Brix GB-BRi7-8550	https://www.ambros.co.uk/computer-shop/gigabyte-brix-gb-bri7-8550-core-i-7-fully-assembled-pc/	OAI D2D has also been successfully operated with the BRi5-8250, but considering additional resources for L3 networking, a BRi7-8550 is suggested.	YES
Radio Front-End	Ettus USRP B210	https://www.ettus.com/product/details/UB210-KIT	Two are needed for LTE-V2X mode 3 or if LTE-V2X Uu is required.	YES
Power Amplifier	Skyworks SKYA21043	https://www.skyworksinc.com/uploads/documents/SKYA21043_	Automotive grade PA for 5.9Ghz 10Mhz up to 23dBm.	NO

Components	Hardware	Link	Notes	Tested
		205246A.pdf		
SMA Cables	Ettus	https://www.ettus.com/all-products/sma-sma/	Need after the PA, and two additional short ones to connect the PA to the USRPs	YES
External Prototype				
Antennas	Ettus	https://www.ettus.com/all-products/vert2450/	Need two antennas per USRP device (Tx and Rx)	NO
Enclosure kit	Ettus Kit	http://www.ettus.com/all-products/usrp-b200-enclosure/	Optional	YES
Synch Pulse	Ettus	https://www.ettus.com/all-products/gpsdo-tcxo-module/	1PPS and 10Mhz sync pulse, in addition to GPS support	NO
Table Prototype				
Synch Pulse	Ettus	https://www.ettus.com/all-products/octoclock-g/	1PPS and 10Mhz replication; This version (-G) comes with an internal GPSDO compliant with USRPs; cost: 1929 euros	YES
Channel Attenuator	Cost		To attenuate the Tx power to a given Rx power and emulate various distances between Tx/Rx	NO
Channel Emulator	Rohde&Schwarz		Generates specific channels as input to USRP devices	NO

The hardware has been selected to match the requirements, but adjustments are expected to be made after test.

OAI ProSe (D2D) in mode 2 (ad-hoc) and relay mode has been successfully been tested using the hardware described in the previous table for the 'Table Prototype'.

4.3 L2 Wireless Software Architecture: OAI Radio Module

This section describes the LTE-D2D and LTE-V2X high-level software architecture. The core components of the ProSe extensions to OAI are shown in Figure 26. The extensions that were made to support ProSe in the Open Air Interface™ (OAI) open source platform will be described below.

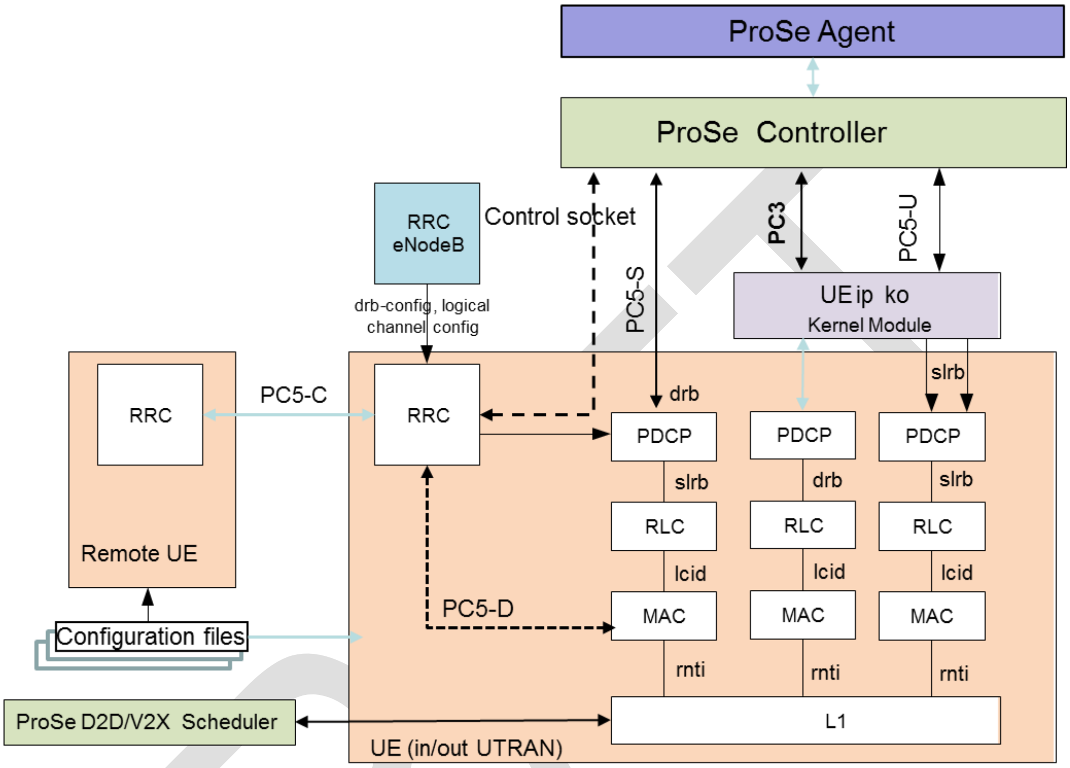


Figure 26. OAI ProSe Extensions

4.3.1 OAI ProSe Extensions Overview

The OAI software is compliant with 3GPP standard specifications. It includes a subset of 3GPP Release 10 features and supports the following LTE entities: UE, eNodeB, and Evolved Packet Core (EPC) that includes the Mobility Management Entity (MME), Home Subscriber Server (HSS), Serving Gateway (SGW), and Packet Data Network Gateway (PGW). To support 3GPP Release 14 ProSe for public safety use, the UE and eNodeB protocol stacks in OAI were extended and new entities were created in the UE and EPC. The white boxes in Figure 26 represent the layers that were already available to support the user plane and control plane for the LTE Uu interface and did not need modification. New protocol layers, functions, or files that were needed to support ProSe such as the sidelink physical layer have been created. Also, existing protocol layers in the UE and eNodeB (e.g., RRC) were modified to support ProSe new PC5 interface:

- PC5-D: The discovery plane of PC5 interface is needed for direct discovery. Discovery allows a UE to discover other UEs that are in proximity. The ProSe Protocol interacts directly with the MAC layer as shown in Figure 26.

- PC5-S: The PC5 signaling protocol stack is used for control plane signaling over the PC5 interface to establish, maintain, and release a secure direct link between two UEs.
- PC5-U: The user plane PC5 interface is used to send traffic directly between two UEs. A UE may establish multiple logical channels, which is not show in Figure 26. A logical channel ID (LCID) included within the MAC subheader uniquely identifies a logical channel within the scope of one Source Layer-2 ID and ProSe Layer-2 Group ID combination. Note that in our OAI ProSe implementation, the IP tables are responsible for IP to sidelink radio bearer (SLRB) mapping. The UE_ip.ko kernel module uses the information provided by the IP tables in order to route each ProSe flow to the right SLRB.
- PC3: The control plane PC3 interface is used for service authorization between the UE and the ProSe Function when the UE is connected to the network (i.e., on-network). The ProSe control signaling is carried over the LTE user plane (i.e., LTE-Uu, S1-U, S5/S8 and SGi) as shown in Figure 26. Note that the PC3 interface is not used when the UE is off-network. In the off-network case, service authorization is pre-configured in the UE.

To support synchronization, new sidelink system information blocks were added per 3GPP TS 36.331. The synchronization information transmitted by the UE may be derived from information/ signals received from E-UTRAN (in coverage) or received from a UE acting as synchronization reference for the transmitting UE. For off-network synchronization, the UE acting as the synchronization reference transmits the *Sidelink Synchronization Signal (SLSS)* and *MasterInformationBlock-SL (MIB-SL)* message via the Sidelink Broadcast Channel (SL-BCH) on the SBCCH logical channel to other UEs in proximity. The MIB-SL carries timing information as well as some configuration parameters such as carrier bandwidth, whether the UE transmitting the MIB-SL is in E-UTRAN coverage, and the frame and subframe numbers in which SLSS and SL-BCH are transmitted.

The network also broadcasts *SystemInformationBlockType18* (SIB18) and *SystemInformationBlockType19* (SIB19) to indicate its support for the sidelink UE information procedure and to provide sidelink communication related resource configuration information in the case of SIB18 and sidelink discovery related resource configuration information in the case of SIB19. When UEs are on-network, they acquire SIB18 and SIB19 and use the resource configuration information provided in these messages as shown in Figure 26. When UEs are off-network, resource configuration information cannot be retrieved from the network and are pre-provisioned in the UE as depicted in Figure 26 by the ProSe Config Files used by the L1 sidelink layer.

The control socket between the Radio Resource Control (RRC) layer in the OAI and the ProSe Application shown in Figure 26 provides PC5-S information, SLRB configuration and logical channel configuration (e.g., LCIDs) to upper layers upon request.

4.3.1 OAI V2X Extensions Overview

According to the technology analysis conducted in [13] and in S4R D1.2 [15], requirements for the WLTB RD cannot be fulfilled entirely by the LTE ProSe D2D or V2X technologies alone. The LTE V2X would provide an enhanced physical layer support as well as a standardized MAC scheduler, but it cannot handle group management, service discovery or unicast communication. LTE ProSe (D2D) on the other hand cannot rely on the broadcast mode if not for Public Safety (PS), and frequencies are restricted either to commercial bands or to Public Safety bands.

Accordingly, S4R2 will follow a hybrid approach: it will rely on the LTE V2X technology, and add the missing management layer (group discovery, service discovery, unicast management) at an overlay layer.

The OAI V2X extensions will therefore consists of three key modifications from the OAI ProSe Extensions:

- LTE V2X Rel. 14 Physical Layer: A different numerology and placement of SL control and data planes is required.
- LTE V2X LTB/SPS scheduler: the LTE V2X rel. 14 default scheduler will be implemented as baseline. Alternative schedulers will also be evaluated.
- LTE V2X non-IP support: LTE V2X support to expose L2 interfaces and L2 addresses.

4.3.2 Logging

Extensive logging information is available using Google logging library such that the ProSe related procedures and data transmission can be examined at all levels of the LTE protocol stack for each type of communication.

4.4 L2 Overlay Software Architecture: Service Module

As mentioned in Section 2, LTE V2X does not support WLTB RD requirements such as service discovery, group management and mesh networking. Accordingly, an Overlay module will be developed on top of the OAI LTE V2X software architecture to provide the missing features.

Figure 27 illustrates the proposed underlay/overlay software architecture. While the underlay architecture corresponds to the OAI LTE V2X software architecture, the overlay integrates three new modules:

- **Group Discovery –** the role is to discover neighboring WLTBN and as function of instructions from the AETBN, form a dedicated group between consists.
- **Service Discovery –** the role is to discover neighboring AETBN services and as function of instructions from the AETBN, form a dedicated group between consists.
- **Mesh Networking –** the role is to handle multi-hop relaying between WLTB RD in a transparent way to the AETBN traffic.

The WLTB Service module will interact with the WLTB Radio module via two APIs:

- **WLTB-C**: the WLTB controlling API, transmitting configuration parameters to the OAI LTE V2X module.
- **WLTB-D**: the WLTB data API, transmitting data packet over the WLTB Radio link.

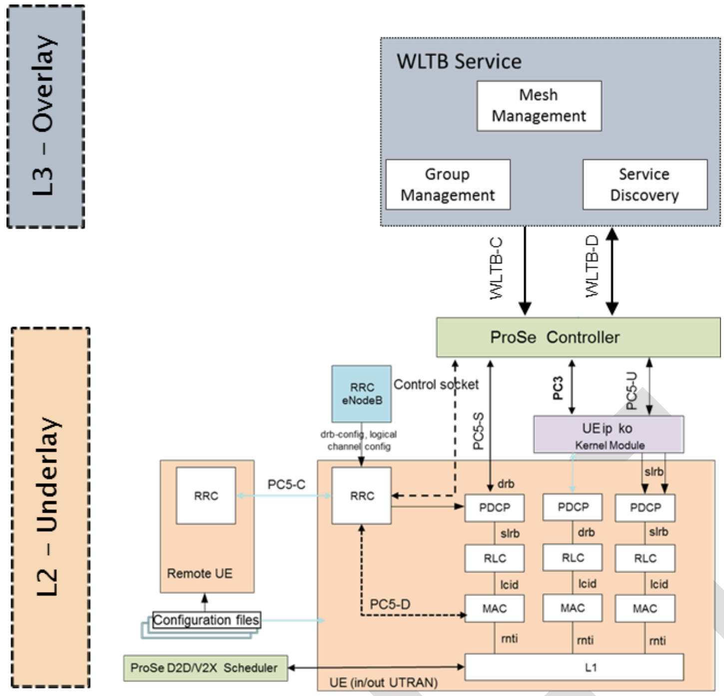


Figure 27 WLTB RD overlay/underlay architecture design

4.4.1 Technology Selection

For the three sub-modules of the WLTB Service module, the following technologies have been selected:

- Service Discovery & Group Management: In order to minimise the divergences between the functional modules of the WLTB RD and the 3GPP specifications (LTE ProSe and NR V2X), the Service discovery and group management will adapt the XML-based LTE ProSe messages specified by 3GPP for LTE D2D.
- Mesh Management: the BATMAN L2 kernel code available at https://openwrt.org/docs/guide-user/network/wifi/mesh/batman.

4.5 WLTB Radio Device Interfaces and Parameters

The WLTB RD is based on LTE-V2X and has been defined with the tight collaboration of CONNECTA 2 project and includes additional functionalities on top of LTE-V2X.

The main characteristics of this interface are listed in Table 10

Table 10: Characteristics of the WLTB RD

OSI Layer	Interface features
1 and 2	Radio link according to LTE-V2X (3GPP release 14)
2	Wireless L2 forwarding protocols • B.A.T.M.A.N-adv Wireless security based on secure password-based authentication and key establishment protocol Simultaneous Authentication of Equals (SAE), RFC 7664.

4.5.1 Physical Layer

Frequency

At the time of writing this document it is not clear which frequency band could be available for the WLTB RD. On the one hand, this system may use ISM bands, however this may involve interferences with other system. Considering the TCMS domain is used to exchange information between train control systems, some of them safety critical, these interference would imply operational availability problems. On the other hand, dedicated band may be used, but nowadays no band has been reserved for this system. Tentatively, and always depending on national regulation and operator willingness to use these bands for this system, the following band could be under the scope in Europe:

- ITS non-safety band 5.855-5.885GHz
- ITS safety band 5.905-5.925GHz dedicated to safety urban rail applications
- Current GSM-R bands
- Future NR V2X bands
- Future new FRCMS bands

For the demonstrator, the ITS Safefy band at 5.895-5.905 GHz will be used.

Transmit Power

According to the distance between the communication partners, the transmission power may be adjusted, providing that the values requested to obey the local regulations are not exceeded. Moreover, depending on the frequency band used and the country in which it is used, the maximum transmission power varies.

According to the ETSI Harmonized Standard EN 302 663, any transmitter for ITS operations in 5.9GHz, any tx device must follow the radiation and spectrum specifications of the ETSI Harmonized Standard EN 302 571.

Additionally, the maximum transmit power is fixed as in Figure 28. The 3GPP LTE V2X rel. 14 shall follow these regulations.

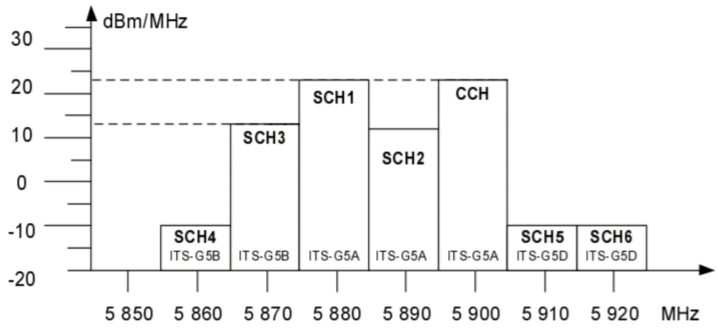


Figure 28: Transmit Power Density Limits ITS channel (source: ETSI EN 302 663)

Considering the WLTB operating on ITS frequency bands, the maximum Transmit limit will be set either as 33dBm EIRP or 23dBm EIRP. However, considering the WLTB operating in mesh topologies, the effective transmit power will be adjusted to maximize the frequency reuse.

Modulation

According to EN 302 663, the default modulation for ITS band (see Figure 29) is 6Mbps, except for the SCH2 having 12Mpbs (considering a reduced Tx power and very short transmit range). The 3GPP LTE V2X rel. 14 reaches 6Mbps for the MCS 6 QPSK ½ (0.48). Considering that LTE-V2X operates in broadcast without HARQ, and considering WLTB will not have a service overlay, the default modulation will be used.

Channel type	Centre frequency	IEEE 802.11 [3] channel number	Channel spacing	Default data rate	TX power limit	TX power density limit
G5-CCH	5 900 MHz	180	10 MHz	6 Mbit/s	33 dBm EIRP	23 dBm/MHz
G5-SCH2	5 890 MHz	178	10 MHz	12 Mbit/s	23 dBm EIRP	13 dBm/MHz
G5-SCH1	5 880 MHz	176	10 MHz	6 Mbit/s	33 dBm EIRP	23 dBm/MHz
G5-SCH3	5 870 MHz	174	10 MHz	6 Mbit/s	23 dBm EIRP	13 dBm/MHz
G5-SCH4	5 860 MHz	172	10 MHz	6 Mbit/s	0 dBm EIRP	-10 dBm/MHz
G5-SCH5	5 850 MHz	182	10 MHz	6 Mbit/s	0 dBm EIRP	-10 dBm/MHz
G5-SCH6	5 910 MHz	184	10 MHz	6 Mbit/s	0 dBm EIRP	-10 dBm/MHz
G5-SCH7	As described in [i.14] for the band 5 470 MHz to 5 725 MHz	94 to 145	several	dependent on channel spacing	30 dBm EIRP (DFS master)	17 dBm/MHz
					23 dBm EIRP (DFS slave)	10 dBm/MHz
NOTE: With respect to emission limits (power limit/power density limit), the more stringent requirement applies.						

Figure 29: European Channel Allocations for ITS

Antenna

In order to guarantee the communication performances, the specifications of the antenna should support MIMO for the used radio bands. The antenna shall be approved according to railway standards (EN 50155, EN 45545-2 and EN 50125-3) and IP 66/ IP 67.

The maximum allowed radiated power depends on the used frequency range and shall conform to local regulations. In Europe, 33dBm EIRP will be used for CCH and SCH1, and 23dBm EIRP for SCH2 as defined by EN 302 663.

These values of the overall radiation power shall not be exceeded by the gain of the antenna.

Hardware Sensitivity Level and Out-of-band Emissions

For radio hardware operating at ITS frequency band, the specifications of the Harmonized Standard EN 302 571 must be enforced. The LTE V2X hardware used for the demonstrator follow these requirements. In particular, a minimum sensitivity limit of -82dBm will be set.

Antenna Cables

In order to guarantee the communication performances, the specifications of the antenna cables shall have an impedance of 50 Ohm and be usable for the LTE (3GPP) frequency bands.

Connectors

Common connectors for antennas shall be used.

4.5.2 Data Link Layer

ARQ

ARQ will not be used for the WLTB (LTE V2X rel. 14 does not support it).

PDU (Frame format)

The PDU will consist of the LTE V2X header encapsulating the WLTB L2 packet. According to LTE V2X specifications for MCS 6, subchannels are multiple of 190 Bytes. Accordingly, WLTB L2 PDUs will have to be padded to match a multiple of 190 Bytes.

MAC Addressing

48 bits MAC addresses will be used. The WLTB Radio device MAC address will be built from the LTE V2X NIC.

L2 forwarding protocol

Packet forwarding will be performed by B.A.T.M.A.N. Advanced (operating in L2). B.A.T.M.A.N will transmit OriGinator Message (OGM) in order to allow WLTB nodes to be discovered by other WLTB nodes. OGM may be relayed over multiple hops. In order to mitigate channel overflowing and traffic congestions, OGM relaying will be limited to the expected number of consists.

According to B.A.T.M.A.N internal rules, a packet will be forwarded to the best mesh 1-hop relay for the target destination WLTB node. In addition to OGM, other link quality management packets will be used to provide additional link quality information.

QoS (Priorities)

LTE V2X uses 8 ProSe (Proximity Services) Per Packet Priorities (PPPP), the lowest PPPP being the most urgent, while the highest PPPP being the less critical. Ethernet also uses 8 priority levels. Accordingly, a one-to-one mapping between L2 prioritization and the LTE V2X PPPP will be applied.

Clock Synchronization

The WLTB Radio Device will have its own clock synchronization mechanism, independently to the AETBN.

Under UTRAN coverage, the eNodeB will provide clock synchronization for the WLTB RD (LTE V2X mode 3). In off-network scenario (LTE V2X mode 4), WLTB RD will synchronize among each other. Synchronization among WLTB RD will be provided by LTE V2X specific signals. WLTB RD will try to select a *SyncRef UE*. If none is found, it will become the *SyncRef UE*. The *SyncRef UE* will send a LTE V2X specific signal called *SLSS* (Sidelink Synchronization Signal) over the LTE V2X sidelink broadcast channel. Any WLTB RD not having themselves a *SyncRef UE* will adopt the timing indicated in the SLSS message of the *SyncRef UE*.

Considering that LTE V2X *SyncRef UEs* are selected mostly considering wireless link reliability, it is unlikely that the WLTB RD being the *SyncRef UE* would also be the AETBN synchronization entity. Accordingly, both synchronization systems should be kept separately.

Traffic Scheduling – Media Access Control

3GPP LTE V2X (rel. 14) in mode 4 (off-network) is based on a Listen-Before-Talk (LBT) MAC with Semi-Persistent Scheduling (SPS). The WLTB RD will use this as default scheduler. In on-network, MAC schedulers are not defined by default, and a basic Priority Scheduling will be implemented. Handovers between on/off networks are not described in LTE Rel. 14 and will not be implemented for the demonstrator. Study on the feasibility and efficiency of such handover will be evaluated.

Train backbone topology discovery

The Train backbone topology will be discovered through the B.A.T.M.A.N. L2 Mesh protocol relying on broadcast originator messages (OGM).

Security Aspects

3GPP LTE V2X does not provide any form of security, and relies on higher layers for securing the WLTB link. Accordingly, the WLTB link will protected by the Secure Password-based Authentication and Key Establishment protocol Simultaneous Authentication of Equals (SAE), according to RFC 7664.

Chapter 5 Summary and Next Steps

This public deliverable is a summary of the confidential and more extended version restricted to the Safe4RAIL2 consortium. It is aimed first at overviewing the various wireless and mesh technologies for the future WLTB and matching them with the requirements identified in D2.1. And secondly, to describe the design architecture of the WLTB RD based on the OpenAirInterface™ platform.

This deliverable thus overviewed key wireless technologies (LTE V2X, ITS-G5, NR V2X, DOT11BD, WiFi, BLE and VLC) as well as mesh technologies (OLSR, AODV, B.A.T.M.A.N., the ETSI Geonetworking).

Considering the wireless technologies, and according to the requirements identified in D2.1, the 3GPP LTE V2X Rel. 14 technologies has been selected for TCMS traffic in the WLTB demonstrator, matching most requirements, and 3GPP NR V2X (5G) will be investigated also for a full match of the requirements. It could yet be noted that the VLC technology has been also identified as a complementary and redundant wireless technology to increase the WLTB robustness.

Considering the mesh technology, and again according to the requirements identified in D2.1, the B.A.T.M.A.N. stateful and proactive mesh technology has been selected. It will be integrated into the WLTB at Link Level (L2), making the wireless link transparent to the AETBN traffic.

Finally, a hardware and software architecture design of the WLTB RD has been provided. In particular, the LTE V2X Rel.14 functionalities supported by the OAI platform have been described, as well as the hardware requirements. Considering that the 3GPP LTE V2X Rel. 14 only partially match the requirements identified in D2.1, a WLTB Service module has been proposed to be added as an overlay over the OAI LTE V2X Rel. 14 implementation.

Chapter 6 List of Abbreviations

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
RN	New Radio
NR	New Radio
OCB	Outside the Context of a BSS
OEM	Original Equipment Manufacturer
PDR	Packet Delivery Ratio
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 11: List of Abbreviations

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