D2.4 – Advanced Wireless Technologies and Applications for Wireless TCMS

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Abstract:	This deliverable summarizes the activities done in WP2 on advanced wireless technologies for wireless TCMS, such as 5G, wireless TSN and Virtual Coupling applications.
Keywords:	T2G, ACS, DbD, TSN, 5G, URLLC, VCTS, T2T, WLTB, WLCN

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Executive Summary

This deliverable summarizes the activities done in several tasks of Safe4RAIL-2 WP2 on advanced wireless technologies for wireless TCMS, including: integration of wireless links of different railway domains (T2.5), extension of Drive-by-Data technology to the Wireless Train Backbone (T2.6), applicability of 5G technology for Wireless Train Backbone and Wireless Consist Network (T2.7), and applicability of Wireless Train Backbone for Virtual Coupling applications (T2.8). The following conclusions have been obtained from these analyses:

1. WLTB and Train-to-Ground (T2G) links can be integrated in the Adaptable Communication System (ACS) device using OpenAirInterface (OAI) technology. Two technical approaches have been presented for this integration.
2. Different options exist for the integration of Time Sensitive Networking (TSN) technology in 5G links, as an enabler for the extension of the Drive-by-Data concept to the WLTB.
3. 5G is a feasible technology for carrying TCMS traffic in the WLTB and the WLCN, while some limitations exist for OMTS traffic. Further analyses should be carried out using worst-case scenarios which are more tailored to realistic wireless TCMS applications.
4. WLTB can be applied for Virtual Coupling applications with a maximum communication distance of 500-1000m. In order to cover longer T2T links for Virtual Coupling a different wireless technology with higher communication range would be needed.

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Chapter 1 Introduction

This deliverable summarizes the activities done in Safe4RAIL-2 on advanced wireless technologies for wireless TCMS, such as DbD or 5G technologies, including results from different tasks in WP2.

The deliverable is structured as follows. Chapter 2 summarizes the analysis done in task T2.5 towards the integration of the Wireless Train Backbone (WLTB) with the Train-to-Ground (T2G) link, providing two different technical approaches for this integration. Chapter 3 includes the study done in task T2.6 for the integration of Drive-by-Data technology in the WLTB, therefore detailing the content of the different Time-Sensitive Network (TSN) standards, as well as the possibilities for the integration of this technology in 5G networks. Chapter 4 presents the applicability of 4G and 5G technology for WLTB and Wireless Consist Network (WLCN), which stems out of Task T2.7. In this chapter both infrastructure-based and V2X versions of 4G and 5G are analyzed against the traffic requirements of the WLTB and WLCN. 3GPP use cases with similar features to those of railways are analyzed first, and custom resource-grid designs are made afterwards. Chapter 5, which is related to Task T2.8, analyses the applicability of WLTB for Virtual Coupling applications. Finally, Chapter 6 presents the conclusions obtained from the works presented in this deliverable.

In summary, this deliverable provides a detailed overview about the future potential that different advanced wireless technologies could bring to the performance of the WLTB and the WLCN.

Chapter 2 Integration of on-board and signalling wireless systems

In this chapter the integration of WLTB with T2G link is analyzed, so that both networks can be covered with the same cellular 4G/5G technology. First the requirements of the T2G link will be obtained, and afterwards two architectural approaches will be presented which allow the simultaneous operation of WLTB and T2G links based on the same technology. Figure 1 illustrates this combined architecture.

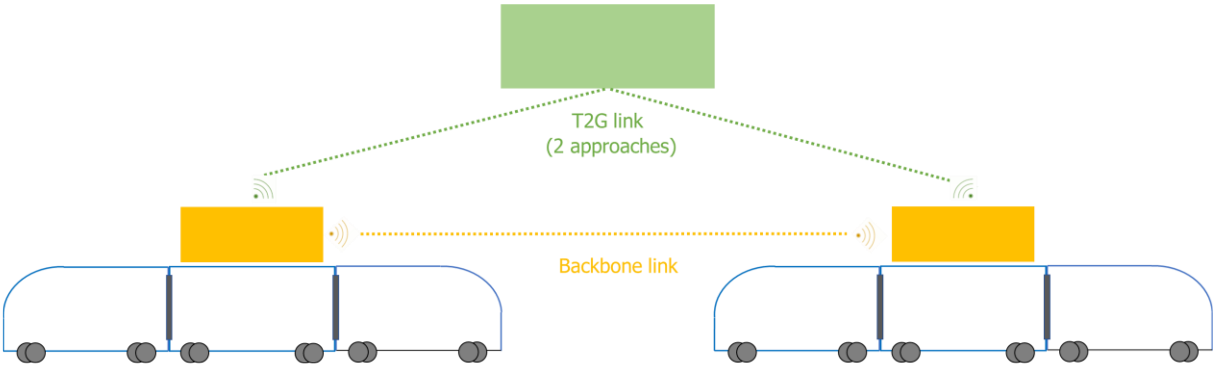
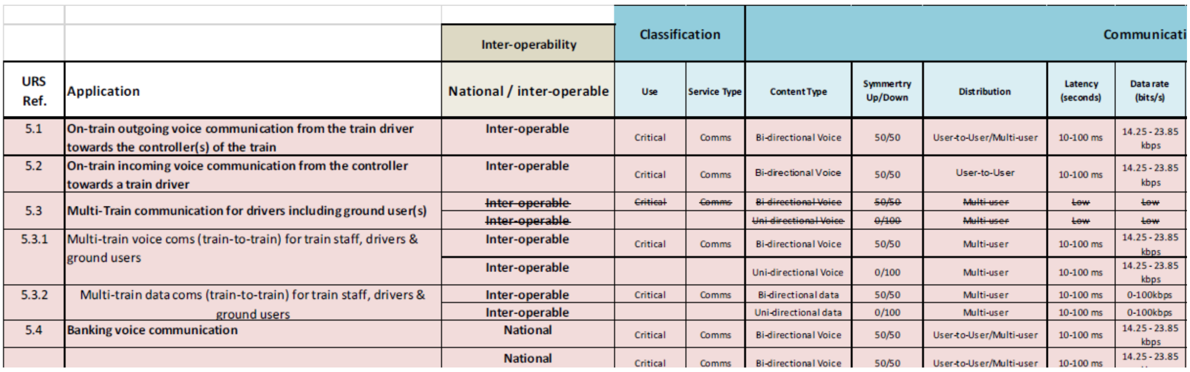


Figure 1. Combination of T2G and WLTB links

2.1 T2G Bit-Rate Requirements

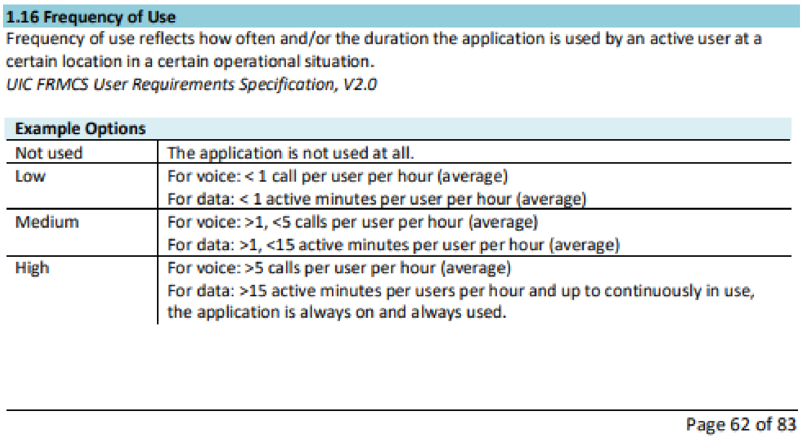
In order to obtain the bit rate requirements of T2G communications, the tables listed in Appendix 5 of D3.1 from X2RAIL-1 have been used, where a set of requirements are detailed for each application used in theT2G link. In this Appendix four tables are listed, according to the type of railway transport sector: Main Line, Regional, Urban/Metro and Freight. Each table contains a set of system requirements and attributes (see example in Figure 2).



		Inter-operability	Classification		Communicati				
URS Ref.	**Application**	**National / inter-operable**	**Use**	**Service Type**	**Content Type**	**Symmertry Up/Down**	**Distribution**	**Latency (seconds)**	**Data rate (bits/s)**
5.1	**On-train outgoing voice communication from the train driver towards the controller(s) of the train**	**Inter-operable**	Critical	Comms	Bi-directional Voice	50/50	User-to-User/Multi-user	10-100 ms	14.25 - 23.85 kbps
5.2	**On-train incoming voice communication from the controller towards a train driver**	**Inter-operable**	Critical	Comms	Bi-directional Voice	50/50	User-to-User	10-100 ms	14.25 - 23.85 kbps
5.3	**Multi-Train communication for drivers including ground user(s)**	~~**Inter-operable**~~	~~Critical~~	~~Comms~~	~~Bi-directional Voice~~	~~50/50~~	~~Multi-user~~	~~Low~~	~~Low~~
		~~**Inter-operable**~~			~~Uni-directional Voice~~	~~0/100~~	~~Multi-user~~	~~Low~~	~~Low~~
5.3.1	Multi-train voice coms (train-to-train) for train staff, drivers & ground users	**Inter-operable**	Critical	Comms	Bi-directional Voice	50/50	Multi-user	10-100 ms	14.25 - 23.85 kbps
		Inter-operable			Uni-directional Voice	0/100	Multi-user	10-100 ms	14.25 - 23.85 kbps
5.3.2	Multi-train data coms (train-to-train) for train staff, drivers & ground users	**Inter-operable**	Critical	Comms	Bi-directional data	50/50	Multi-user	10-100 ms	0-100kbps
		Inter-operable			Uni-directional data	0/100	Multi-user	10-100 ms	0-100kbps
5.4	**Banking voice communication**	**National**	Critical	Comms	Bi-directional Voice	50/50	User-to-User/Multi-user	10-100 ms	14.25 - 23.85 kbps
		National	Critical	Comms	Bi-directional Voice	50/50	User-to-User/Multi-user	10-100 ms	14.25 - 23.85

Figure 2 Snapshot from X2RAIL-1 D3.1 Appendix 5

In order to get the requirements of T2G, out of all attributes, data rate and latency have been selected. Data rate values have been scaled according to their frequency of use (low, medium, or high), which is defined in the glossary of the appendix (see Table 1).



1.16 Frequency of Use

Frequency of use reflects how often and/or the duration the application is used by an active user at a certain location in a certain operational situation.

UIC FRMCS User Requirements Specification, V2.0

Example Options	
Not used	The application is not used at all.
Low	For voice: < 1 call per user per hour (average) For data: < 1 active minutes per user per hour (average)
Medium	For voice: >1, <5 calls per user per hour (average) For data: >1, <15 active minutes per user per hour (average)
High	For voice: >5 calls per user per hour (average) For data: >15 active minutes per users per hour and up to continuously in use, the application is always on and always used.

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Table 1. Frequency of use

In order to obtain the total data rate for an application classified with a "low" frequency of use, the following process has been applied:

1. To sum up all the data rates which have a frequency of use qualified as "low".
2. To multiply the outcome by 1/60 (1 active minute per hour).

Similarly, in the case of "medium" frequency:

1. To sum up all the data rates which have a frequency of use qualified as "medium".
2. To multiply the outcome by 5/60 for voice and 15/60 for data.

The same reasoning has been followed for "high" frequency of use.

It must be noted that this procedure represents a worst case, because it is being assumed that all applications are transmitting at the same time and at its maximum rate.

Obtained results for T2G data rate and latency are summarized in Table 2, and graphically for data rate in Figure 3. These values have been obtained for different railway sectors (Main Line, Regional, Urban and Freight), different operation locations (Station, Yard or Line), and different operation modes (Normal, Degraded and Emergency). It can be observed that the highest data rate requirements for the T2G link are for Urban trains in Station and Line in Normal mode, mainly for real time video (non-critical) applications and internet for passengers.

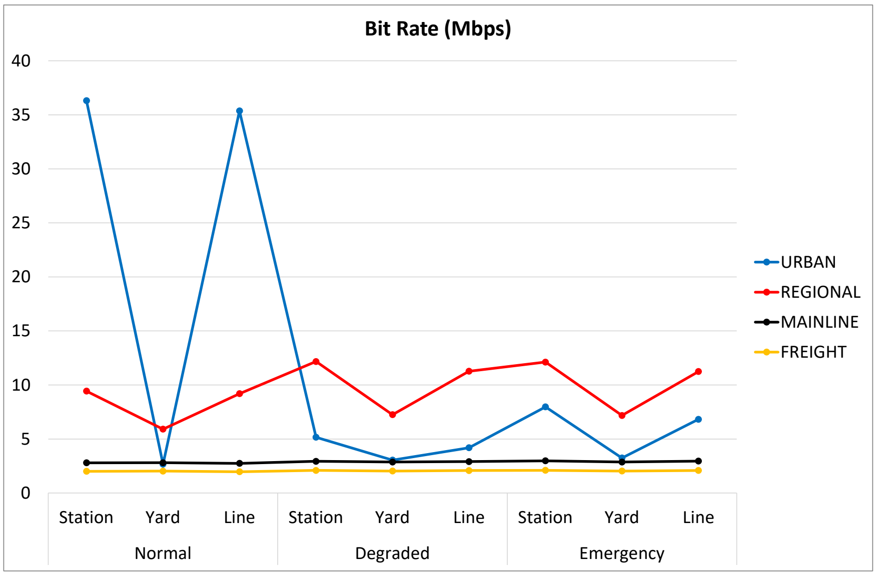

Figure 3 T2G Requirements (graphical outcomes)

			DATA RATE (Mbps)	LATENCY min (msec)	LATENCY max (msec)
Main Line	**Normal**	**Station**	2.8	10	500
		Yard	2.8		
		Line	2.7		
	Degraded	**Station**	2.9		
		Yard	2.8		
		Line	2.9		
	Emergency	**Station**	2.9		
		Yard	2.8		
		Line	2.9		
Regional	**Normal**	**Station**	9.4	10	3500
		Yard	5.9		
		Line	9.2		
	Degraded	**Station**	12.2		
		Yard	7.2		
		Line	11.2		
	Emergency	**Station**	12.2		
		Yard	7.2		
		Line	11.2		
Urban	**Normal**	**Station**	36.3	10	2000
		Yard	2.7		
		Line	35.3		
	Degraded	**Station**	5.2		
		Yard	3.0		
		Line	4.2		
	Emergency	**Station**	8.0		
		Yard	3.3		
		Line	6.9		
Freight	**Normal**	**Station**	2.0	10	500000
		Yard	2.0		
		Line	2.0		
	Degraded	**Station**	2.0		
		Yard	2.0		
		Line	2.1		
	Emergency	**Station**	2.1		
		Yard	2.0		
		Line	2.1		

Table 2 T2G Requirements

2.2 Integration Architecture Proposals

Figure 4 shows an integration proposal from CONNECTA-2 project in order to integrate WLTB and T2G communications, via the Adaptable Communication System (ACS). In the following sections, two proposals will be presented in order to combine WLTB and T2G traffic using the same radio technology in the ACS.

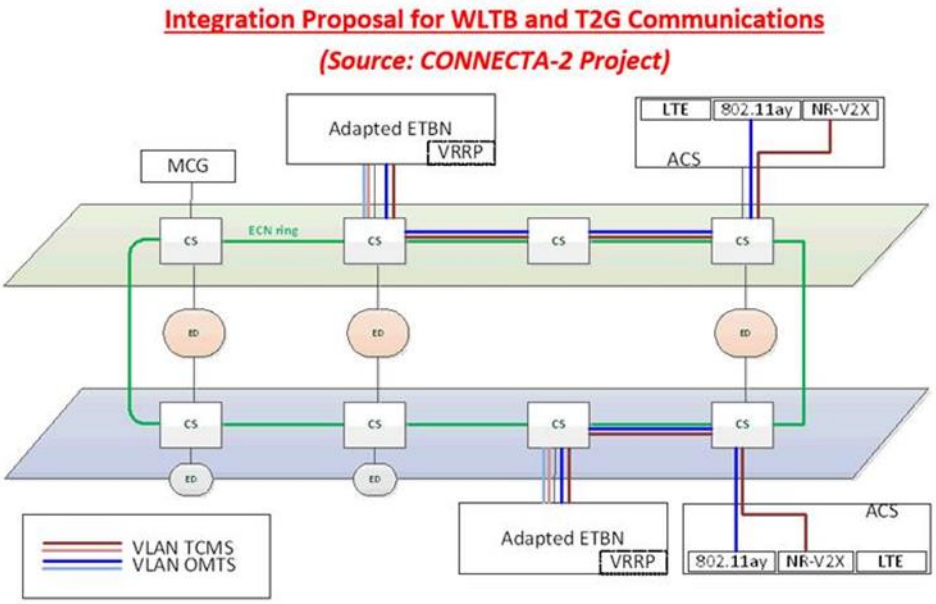

Figure 4 WLTB and T2G communications proposal

2.2.1 LTE/5G dongle connected to OAI

One approach for WLTB/T2G integration is to equip with a commercial LTE dongle the WLTB Radio Device (RD) from Safe4RAIL-2. A bridge will split the traffic between Uplink/Downlink (UL/DL) and Sidelink (SL) either to the WLTB or to the T2G wireless link. Traffic separation between critical signalling (TCMS) and other on-board traffic (OMTS) is done with a bridge inside the embedded computer. Considering that LTE V2X (rel.14) does not support strict traffic prioritization, two wireless links are used between critical signalling and on-board traffic. Critical signalling is sent by the bridge to the LTE V2X interface, whereas on-board traffic is sent to the WiFi interface. This approach is depicted in Figure 5.

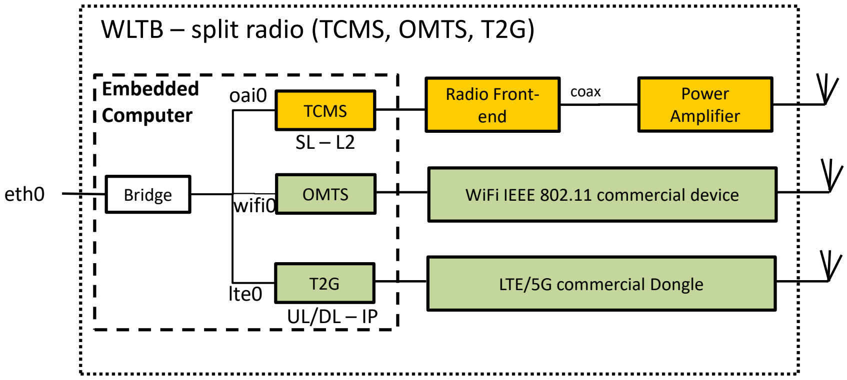

Figure 5 WLTB split radio architecture

The cellular ground infrastructure could either be a commercial operator or an OAI eNodeB. Although LTE dongle can connect to OAI, one issue is the available frequency on which OAI could operate. In a laboratory, OAI has leeway to operate on cellular spectrum, but on open-field, spectrum would need to be reserved. An additional advantage of this split architecture is that the dongle could also be 5G, therefore enabling 5G communication on the T2G wireless link.

The frequencies for LTE-V2X[1] Sidelink are explicitly assigned by 3GPP and separated from uplink communications. Sidelink frequencies are not expected to be explicitly assigned and it is possible that sidelink and uplink traffic share the same spectrum. Accordingly, joint WLTB and T2G could be operating on the same frequency spectrum, either in separated 5G resource pools (orthogonal SL and UL/DL resources) or jointly using the same resources (spectrum reuse). The latter strategy is however not likely to be possible, as considering the significant capacity required by T2G communication, UL/DL resources are not expected to be easily reused. Also, the available 5G capacity for T2G should be leveraged considering that part of its UL/DL spectrum should be allocated for WLTB. A dedicated study should be conducted to evaluate the potential coexistence between WLTB and T2G on the spectrum. As function of the outcome of this study, dedicated 5G Sidelink (V2X) spectra should be allocated for WLTB.

2.2.2 Additional USRP Device

The OAI ProSe code supports both infrastructure and ad-hoc modes. Considering that the OAI Prose infrastructure mode makes SL control packets go over the eNB, while SL data packet directly to the target UE, OAI supports dual links:

- UL/DL for ProSe and LTE infrastructure communications
- SL for Prose SL communications

Although the USRP B210 modules have a 2x2 MIMO feature, considering that the radio frequency for the UL/DL (2.7GHz or 3.6GHz) differs from the SL (5.9GHz), two USRP devices would be required for this architecture. As depicted in Figure 6, OAI supports a connection of two USRP on a single OAI instance, and creates two different sockets:

- oai0 – socket to receive SL traffic
- oai1 – socket to receive UL/DL traffic

Accordingly, a potential WLTB radio device with dual radio for WLTB and T2G could be designed according to Figure 6, where a bridge will be in charge of directing ETBN or OMTS traffic either to the WLTB or to the T2G wireless link.

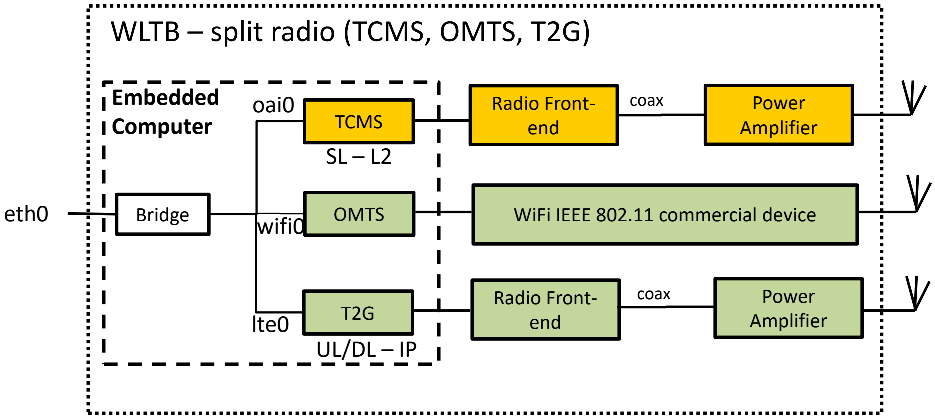

Figure 6 WLTB dual radio architecture

OAI is being extended to support 5G, primarily using a 5G commercial phone or dongle, but a OAI 5G UE will be available by the end of 2021. Figure 6 is therefore expected to be also valid considering 5G networks.

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[1] Note that LTE-V2X and 4G-V2X are used indistinctively throughout the document. The same applies to 5G-V2X and NR-V2X.

Chapter 3 DbD concept evolution towards wireless Train Backbone

In this Chapter it is analyzed how the Drive-by-Data (DbD) technology, based on Time-Sensitive Networking (TSN), could be integrated in the WTLB. For this, the TSN standards are detailed first. Afterwards, the applicability of these standards in industrial application is detailed, and several approaches are described for the integration of TSN standards with 5G technology. Finally, the requirements of the Adapted-ETBN related to TSN technology are analyzed.

3.1 TSN Standards

Time-Sensitive Networking (TSN) [1] is a set of IEEE 802 sub-standards with the objective of providing deterministic communication with real-time (RT) guarantees over Ethernet. TSN is an extension of traditional Ethernet data-link layer. The main features provided by TSN are oriented to resource management, reliability, access control and time synchronization [2]:

1. *Resource management:* IEEE 802.1Qcc sub-standard defines three different management models.
2. *Reliability:* TSN provides reliable communications with IEEE 802.1CB sub-standard, which transmits multiple copies of the same packet over different paths and with IEEE 802.1Qci sub-standard which protects bandwidth violation, malfunctioning and malicious behaviour.
3. *Access control:* TSN introduces a traffic shaper (IEEE 802.1Qbv) in order to guarantee the worst-case latency for critical data.
4. *Time synchronization:* TSN proposes the use of the generalized Precision Time Protocol or gPTP (IEEE 802.1AS) in order to get an accurate time synchronization across the network. The IEEE 802.1AS sub-standard is also necessary for the proper operation of other TSN sub-standards such as IEEE 802.1Qbv [2].

These standards are described in detail in the following sections.

3.1.1 Resource management (IEEE 802.1Qcc)

In order to meet the configuration requirements of industrial and automotive systems, TSN provides through IEEE 802.1Qcc mechanisms to improve the existing reservation protocols such as Stream Reservation Protocol (SRP). The configuration requirements to meet are among others bandwidth reservation, synchronization and redundancy. On the other hand, the IEEE 802.Qcc provides a set of tools to manage and control the TSN network.

IEEE 802.1Qcc enhances the existing SRP protocol with a User Network Interface (UNI). UNI provides a common method to request Layer 2 services and is used to exchange configuration information between the user and the network side of this interface. On the user side, there are Talkers and Listeners which are TSN users and TSN end stations. Conversely, on the network side there are TSN bridges. Having this into account, the devices in the user side, will specify the requirements of the traffic flows they wish to transmit. The specification of the requirements will be made without knowing all the details about the network such as the number of end systems and switches or the latency of the network. Then, the network will analyse the information provided by the devices in the user side along with the network capabilities. With this analysis, the network will configure the TSN bridges in the network side to meet the requirements of the devices in the user side.

To make this possible, in IEEE 802.1Qcc sub-standard three different configuration models are considered:

1. **Fully distributed model**: as can be seen in Figure 7, in this configuration model, the UNI is located between TSN users/TSN end station and the TSN bridge to which they are connected. Each TSN device in the user side transmits its requirements to the TSN bridge to which it is connected. Then, each TSN bridge propagates the TSN user and the network configuration to the neighbouring bridge(s). Bridges are the responsible to manage resources locally, so they do not have complete information of the network. As a result of this, the traffic shaper proposed in the IEEE 802.1Qbv sub-standard cannot be applied properly. Moreover, the configuration of the TSN user side devices is not addressed with this configuration model.

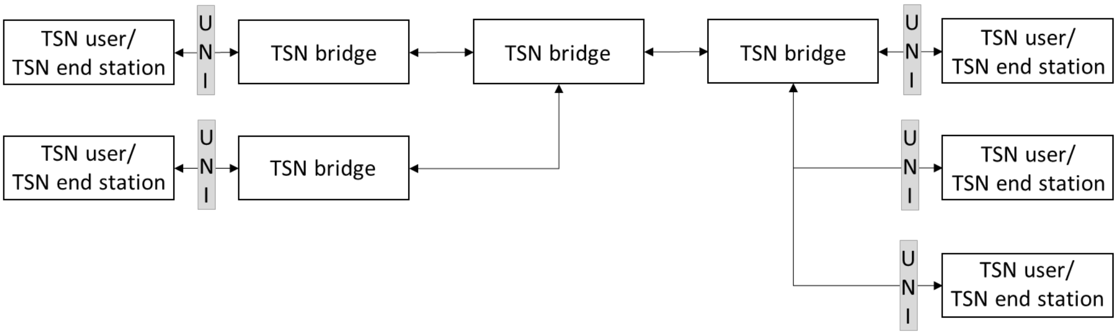

Figure 7: IEEE 802.1Qcc fully distributed model.

2. **Centralized network/Distributed user model**: in this model, a Centralized Network Configuration (CNC) entity is introduced as can be seen in Figure 8. The CNC will be connected to all the TSN bridges in the network. The UNI is also located between TSN users/TSN end station and the TSN bridge to which they are connected. Unlike in the fully distributed model, in this model the TSN bridges communicate the user requirements directly to the CNC along with their capability and topology information. In this way, CNC has a complete view of the TSN network and thus it can configure the TSN bridges having more information about the network than in the fully distributed model. The CNC will provide the configuration information (such as the information to configure the traffic shaper proposed in the IEEE 802.1Qbv sub-standard) to each bridge in the path between the involved TSN end stations to fulfil TSN stream requirements. Even so, following this configuration model, the configuration of the TSN user side devices cannot be done using the CNC either.

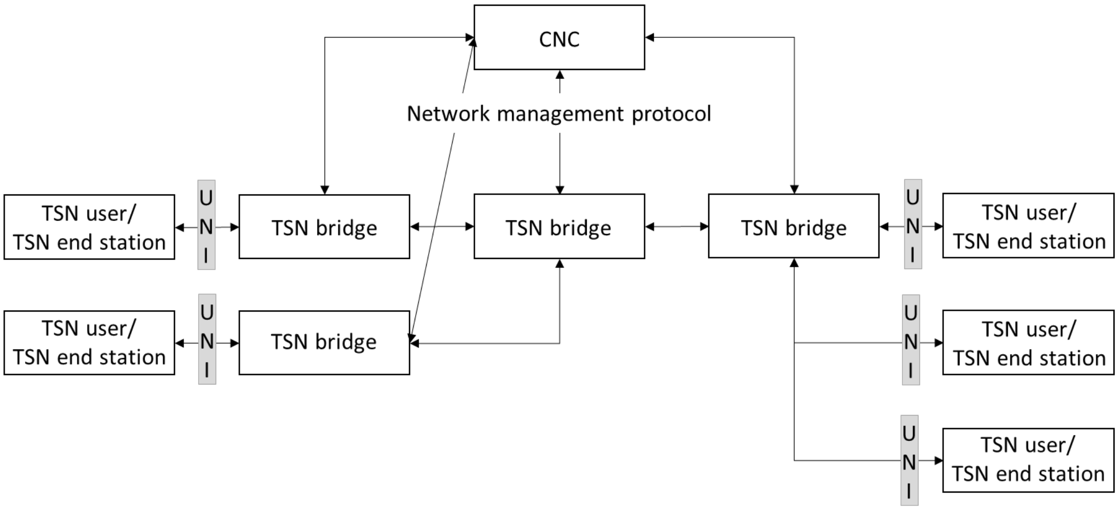

Figure 8: IEEE 802.1Qcc centralized network/distributed user model.

3. **Fully centralized model**: as it is seen in Figure 9, this configuration model is similar to the previous ones. The main difference is the addition of a Centralized User Configuration (CUC) entity in order to address the configuration of the TSN user side devices. In this configuration model, the UNI is located between the CUC and the CNC. As in centralized network/distributed user model configuration model, the CNC will be connected to all the TSN bridges in the network. However, the UNI will be the located only between the CUC and the CNC. Moreover, the CUC will be connected to all the TSN user side devices. In this configuration model, TSN user side devices will communicate their requirements directly to the CUC and the CUC may adapt the end station requirements before forwarding them to CNC. The information exchange between the CUC and the CNC will be carried out through the UNI. It can be used to discover end stations, to recover the end station capabilities, and to configure TSN functions with optimized delay at end stations. This fully centralized configuration allows a higher degree of coordination of the whole network to better meet the requirements of the TSN flows. That is why this configuration is intended for critical applications. Moreover, this configuration model allows a dynamic scheduling of TSN networks.

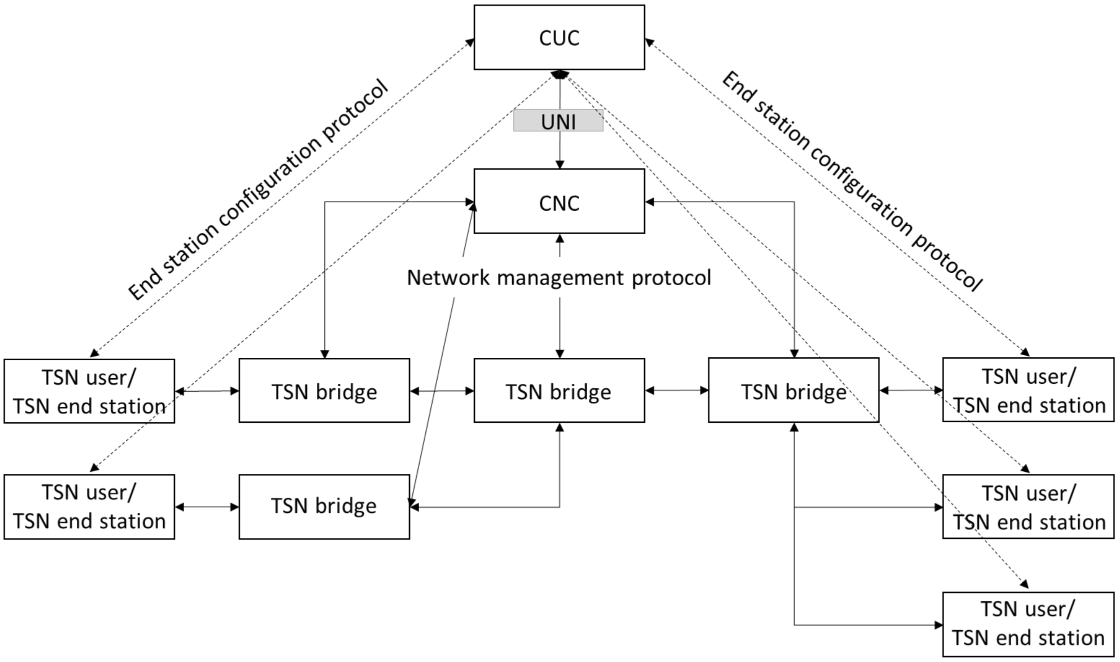

Figure 9: IEEE 802.1Qcc Fully Centralized Model.

3.1.2 *Reliability (IEEE 802.1CB and IEEE 802.1Qci)*

To provide robust and reliable communication, a redundancy management mechanism is defined by IEEE 802.1CB sub-standard. This mechanism is similar to Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR) approaches. TSN uses IEEE 802.1CB sub-standard that consists of transmitting redundant copies of a message at the same time from different disjointed paths. Note that in order to use the mechanism proposed by IEEE 802.1CB sub-standard, the fully centralized model proposed by IEEE 802.1Qcc sub-standard is required.

In the case that both messages reach the receiver, the duplicated message is discarded whereas, if the original message does not arrive correctly, the receiver uses the transmitted copy. It does not use retransmissions at link level, but it can use retransmissions at application layer. Moreover, to minimize network congestion, message replication can be done only for critical traffic.

Linked to the IEEE 802.1CB sub-standard, the IEEE 802.1Qci sub-standard will provide the ability to filter frames at input ports based on their arrival time, data rate and bandwidth. With this the effects of the nodes that act incorrectly want to be limited and avoid overload situations.

The IEEE 802.1Qci proposes that, when a frame reaches the input port it must go through three filters. The flow is filtered first according to the defined policies. The frames are matched with permitted stream ID and priority level. Then a regulating mechanism regulates the flow. For that all streams are coordinated so that all frames are processed in an orderly and deterministic fashion. Finally, the bandwidth limitations of the flow are ensured before a frame is queued for forwarding.

3.1.3 *Access control (IEEE 802.1Qbv)*

In order to guarantee the worst-case latency for critical data, the IEEE 802.1Qbv sub-standard introduces a traffic shaper. This sub-standard is the core of TSN and its aim is to transmit high priority traffic packets in a bounded time. To do this, the Ethernet traffic is divided into different classes and their transmission is scheduled using a TDMA mechanism so that the access time to the channel is limited. This concept is called in TSN as Time-Aware Shaper (TAS) that uses the principle of time-triggered communication. The TAS enables to control the flow of queued traffic from a TSN-enabled switch. For that, it follows three steps:

1. When data comes to a TSN switch, it is forwarded to the corresponding egress port.
2. In each port, data is classified in different queues based on the traffic class in first in first out (FIFO) way. On each there can be up to 8 queues with different priorities, so packets are filtered according to their priority. The queues will be previously defined within a scheduler, and the transmission of the packets will take place during a scheduled time window. During these time windows, queues that are not transmitting will be blocked to ensure that non-scheduled traffic is not being transmitted.
3. The queues are controlled by Gate Control Lists (GCL) that determine which queues are opened or closed to be transmitted or buffered at each time instant. If there are more than one queues opened at the same time, the forwarding of frames will depend on the priority of the queue. The principal idea is to separate the critical traffic from the best effort traffic.

Taking all of this into account, packets in a queue can be transmitted when:

- A queue is open.
- If there are no other queue open with higher priority and with a packet prepared.
- If the frame can be transmitted within the time window in which the queue is open.

Moreover, in order to isolate best effort (BE) traffic from critical traffic and avoid collisions between them, IEEE 802.1Qbv sub-standard introduces a guard band whose length is the maximum duration of the BE packet transmission time. The introduction of this guard band reduces the latency of high priority packets, although decreases resource efficiency.

3.1.4 Time synchronization (IEEE 802.1AS)

Some of the TSN sub-standards mentioned above require precise time synchronization throughout the network, that is, an established common time reference that is shared by all entities in the TSN network. Time synchronization is needed for example for a proper operation the TAS procedure defined in IEEE 802.1Qbv sub-standard. In TSN, time synchronization is accomplished through the IEEE 802.1AS Time Synchronization for Time Sensitive Applications sub-standard that uses a specialized profile of IEEE 1588-2008 (1588v2) [3], the generalized Precision Time Protocol (gPTP). The gPTP protocol synchronizes clocks between network devices by exchanging relevant time event messages. In turn, this protocol is based on a master/slave configuration. Taking this into account, three types of devices are defined:

1. *GrandMaster (GM):* there is one for each time domain and is defined as the bridge with the most accurate clock source. It is selected by the Best Master Clock Algorithm (BMCA). The main function of the GM is to periodically initiate the clock synchronization and transmit this information from a master port connected to the time domain.
2. *Bridge (Boundary clock):* it has a slave port to receive the synchronization messages of another component, and it has one or several master ports to send synchronization messages to other devices.
3. *Slave:* it gets the time synchronization information to synchronize the nodes to the GM reference. It has a slave port to collect synchronization information. In a time domain, there can be multiple slave devices.

3.2 Industrial Applications vs WLTB Requirements

The Industrial Internet Consortium (IIC) defines typical traffic types in industrial environments and recommends which TSN mechanisms should be advisable to develop in order to support these traffic types in a converged network [3]. The traffic types are separated attending to several characteristics, such as data transmission periodicity, synchronization to network time at application layer, data delivery constraints, tolerances to loss, size and criticality:

1. *Isochronous*: traffic that applies to pairs that need to be synchronized and exchange traffic at a certain cycle time. Also requires of minimal jitter and external interference, with a guaranteed delivery bound time. Usually has fixed payload sizes.
2. *Cyclic*: this category refers to traffic that involves periodic communication, but without needing a synchronization to a common time. Messages can be distributed along the cycle time or clustered together depending on the topologies, but within a latency boundary and usually with fixed message sizes.
3. *Events (Alarms and Operator/Control)*: this traffic is occasional and occurs when a variable change requires attention. This traffic could be just a single message or a burst, but with low tendency to lose messages. Traffics are separated depending on latency and payload size requirements into “Alarms” and “Operator and Control”.
4. *Configuration & Diagnostics*: traffic that specifies the status of a system or a specific configuration to be applied. It usually provides mechanisms to survive to message recovery data.
5. *Network control*: network control messages which do not have high payload size but must be delivered under critical delivery requirements.
6. *Best effort traffic*: the default traffic is transported using this kind of traffic; it can suffer losses if higher priority traffic needs to be exchanged.
7. *Video*: Streaming traffic between two endpoints. This traffic represents video streaming which does not have extremely high-performance requirements.
8. *Audio/Voice*: similar to the previous one, but with even lower performance requirements.

Table 3 summarizes the features of all these traffics.

Types	**Periodicity**	**Typical Period**	**Synchronized to network**	**Data Delivery Guarantee**	**Tolerance to interference**	**Tolerance to loss**	**Typical application data size (bytes)**	**Criticality**
Isochronous	Periodic	<2ms	Yes	Deadline	0	None	Fixed: 30~100	High
Cyclic	Periodic	2~20ms	No	Latency (100µs~2ms)	<=Latency	1~4 frames	Fixed:50~1000	High
Events: Alarms & Operator Commands	Sporadic	n.a.	No	Latency	<=Latency	Yes	Variable: 100~1500	Medium
Events: Control	Sporadic	n.a.	No	Latency	<=Latency	Yes	Variable: 100~200	High
Network Control	Periodic	50ms~1 s	No	Bandwidth	Yes	Yes	Variable: 50~500	High
Config & Diagnostics	Sporadic	n.a.	No	Bandwidth	n.a.	Yes	Variable: 500~1500	Medium
Best Effort	Sporadic	n.a.	No	None	n.a.	Yes	Variable: 30~1500	Low
Video	Periodic	Frame rate	No	Latency (10ms)	n.a.	Yes	Variable: 1000~1500	Low

Types	**Periodicity**	**Typical Period**	**Synchronized to network**	**Data Delivery Guarantee**	**Tolerance to interference**	**Tolerance to loss**	**Typical application data size (bytes)**	**Criticality**
Audio/Voice	Periodic	Sample rate	No	Latency (40 ms)	n.a.	Yes	Variable: 1000~1500	Low

Table 3 Traffic types in industrial applications [3]

Taking into account these requirements for industrial traffics, we can easily match them with the requirements defined by CONNECTA-2 for the different traffic types in the WLTB. Moreover, in [3] the TSN standards that can be applied to each industrial traffic are also detailed. This means that combining these two pieces of information we can indirectly map the TSN standards to the WLTB traffics. This analysis is presented in Table 4.

This first method shows an approximation on which TSN standards would be required for the different traffics in the WLTB.

INTER-CONSIST (WLTB) REQUIREMENTS			**INDUSTRIAL TRAFFIC REQUIREMENTS**									**802.1Qbv (exclusive gating)**	**802.1AS Rev (Clock Synch)**	**Cut-through**	**802.1CB - Frame Replication**	**802.1Qbu Frame preemption**	**802.1Qci (Ingress Policing)**	**802.1Qav (CBS)**	**802.1Qat**
SCOPE	**DATA CLASS**		**Types**	**Periodicity**	**Typical period**	**Synchronized to network**	**Data Delivery Guarantee**	**Tolerance to interference**	**Tolerance to loss**	**Typical Application data size (Bytes)**	**Criticality**								
INTER-CONSIST	Process Data	Time sensitive	Isochronous	Periodic	< 2ms	Yes	Deadline	0	None	Fixed: 30 ~ 100	High	M	M	O	O		M^{T}		M
			Cyclic	Periodic	2~20ms	No	Latency	<=Latency	1~4 frames	Fixed: 50 ~ 1000	High								
		Normal	Cyclic	Periodic	2~20ms	No	Latency	<=Latency	1~4 frames	Fixed: 50 ~ 1000	High	M	M		O		M^{R}		M
			Alarms & Operator Commands	Sporadic	n.a	No	Latency	<=Latency	Yes	Variable: 100 ~ 1500	Medium								
	Message Data		Alarms & Operator Commands	Sporadic	n.a	No	Latency	<=Latency	Yes	Variable: 100 ~ 1500	Medium								
			Config & Diagnosis	Sporadic	n.a	No	Bandwidth	n.a	Yes	Variable: 500 ~ 1500	Medium					O	M^{R}		M
	Supervisory Data		Network control	Periodic	50ms ~ 1s	No	Bandwidth	Yes	Yes	Variable: 50 ~ 500	High			C		C			
			Control	Sporadic	n.a	No	Latency	<=Latency	Yes	Variable: 100 ~ 200	High								

INTER-CONSIST (WLTB) REQUIREMENTS			**INDUSTRIAL TRAFFIC REQUIREMENTS**									**802.1Qbv (exclusive gating)**	**802.1AS Rev (Clock Synch)**	**Cut-through**	**802.1CB - Frame Replication**	**802.1Qbu Frame preemption**	**802.1Qci (Ingress Policing)**	**802.1Qav (CBS)**	**802.1Qat**
SCOPE	**DATA CLASS**		**Types**	**Periodicity**	**Typical period**	**Synchronized to network**	**Data Delivery Guarantee**	**Tolerance to interference**	**Tolerance to loss**	**Typical Application data size (Bytes)**	**Criticality**								
	Streaming Data	Audio	🟥 Video	Periodic	Frame Rate	No	Latency	n.a	Yes	Variable: 1000 ~ 1500	Low								
			🟩 Audio/Voice	Periodic	Sample Rate	No	Latency	n.a	Yes	Variable: 1000 ~ 1500	Low					O	M^R	R	M
		Video	🟩 Video	Periodic	Frame Rate	No	Latency	n.a	Yes	Variable: 1000 ~ 1500	Low					O	M^R	R	M
			🟥 Audio/Voice	Periodic	Sample Rate	No	Latency	n.a	Yes	Variable: 1000 ~ 1500	Low								
	Best Effort Data		🟩 Best effort	Sporadic	n.a.	No	🟩 None	🟩 n.a	🟩 Yes	🟥 Variable: 30 ~ 1500	Low					O			

🟥 Industrial traffic requirements that do not meet WLTB traffic requirements
🟩 Industrial traffic requirements that meet WLTB traffic requirements

M: Mandatory; O: Optional; C: Conditional; R: Recommended; T: Time-based; R: Rate-based

Table 4 CONNECTA-2 WLTB requirements vs Industrial traffic vs TSN standards

3.3 Integration of TSN Technology in 5G

Currently there are no 3GPP proposals for integration of TSN with 4G or 4G-V2X; however, 5G Ultra-Reliable and Low Latency Communication (URLLC) capabilities provide a good match for TSN features. These two key technologies can be combined and integrated to provide deterministic connectivity end to end. Several options for this are presented in this section.

3.3.1 Architecture

The 5G system (5GS) may be operated as a standalone TSN network or part of a TSN network. In both cases, it is essential that the 5GS solution supports the three TSN configuration models defined in the IEEE P802.1Qcc standard: Fully distributed model, Centralized Network/Distributed User Model and Fully Centralized Model. The Fully Centralized Model (described in section 3.1.1) is the most appropriate one for critical data applications and 5G/TSN integration [4].

For the integration of 5G with TSN, two possible architectures can be considered according to the 3GPP technical report TR 23.734 [5]. In the first case, the 5G system is considered as a TSN link whereas in the second case the 5G system is considered as a TSN bridge within the TSN network. In the first one (see Figure 10), the link model used in TSN is quite simplistic, as it uses a limited set of attributes to characterize the link.

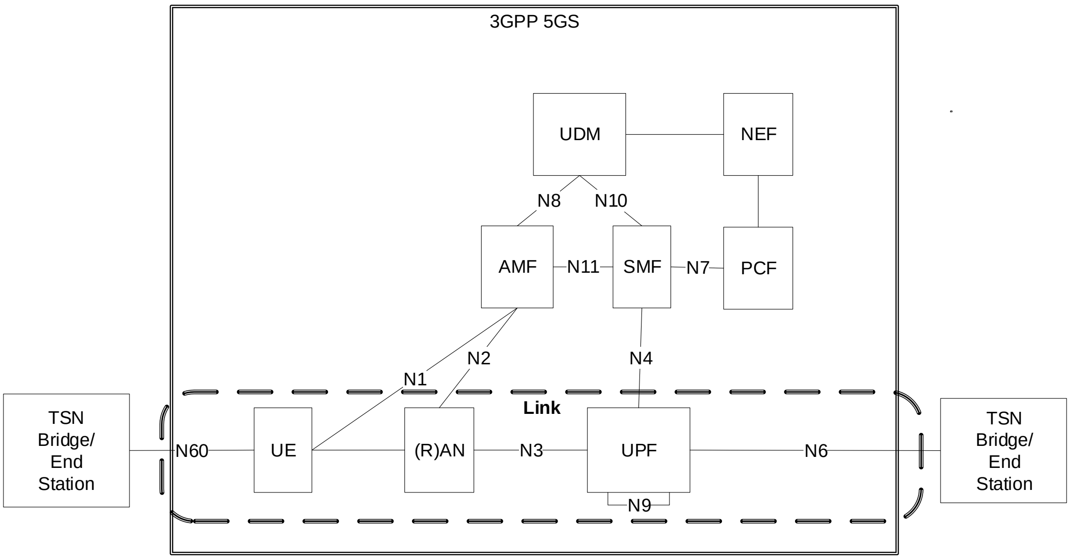

Figure 10: 5G system as a TSN link [5]

In the second one (see Figure 11), the 5G System is considered as a black box from the TSN viewpoint. This second approach is easier since it adopts the specified quality of service framework of the 3GPP 5G System and there is no explicit need for any of the 3GPP network nodes to support TSN protocols and procedures that are part of the external TSN system. Therefore, this is the recommended approach for the integration of TSN and 5G networks.

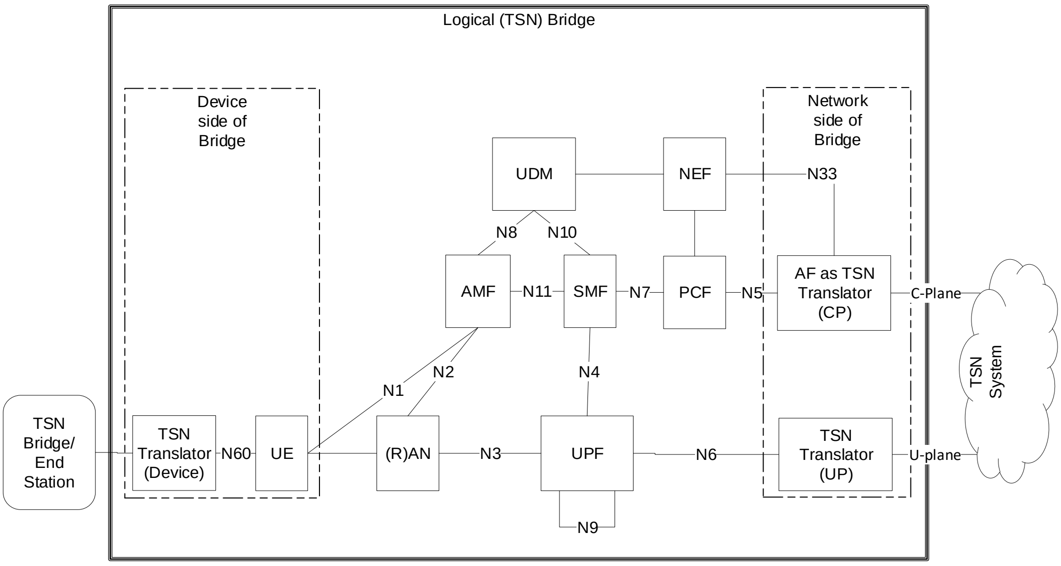

Figure 11: 5G system as a TSN bridge [5].

In Table 5, the main advantages and disadvantages of both architecture models are summarized.

	Considered architectures	
	5G system as a TSN link	**5G system as a TSN bridge**
Advantages	The link model used in TSN it is quite simplistic, it uses a limited set of attributes to characterize the link.	The 5G system is considered as a black box from the TSN viewpoint.
Disadvantages	The 5G system doesn't behave like an Ethernet cable but still would need to expose its capabilities according to the limited possibilities of the TSN link model.	The 5G system can use TSN internally but it cannot interact with TSN nodes outside of 5G system.

Table 5. Advantages and disadvantages of the considered architectures

3.3.2 Translators

In the architecture in which the 5G system is considered as a TSN bridge, some translators are needed in order to exchange information between both networks. These translators are responsible, among other tasks, for carrying out the functions of the 802.1AS standard. As can be seen highlighted in Figure 12, these translators are implemented in specific points of the 5G network both in the user and control planes (U-plane and C-plane).

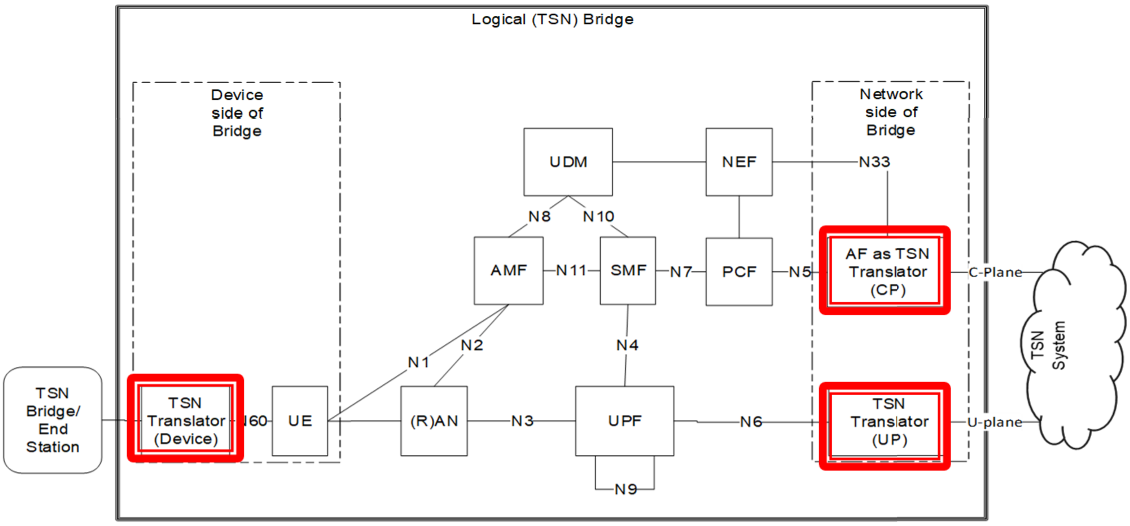

Figure 12: Translators in an architecture in which the 5G system is considered as a TSN bridge [5]

The translators must exchange information in order to manage the 5G network. For example, the input and output ports of the translator should have information about the TSN scheduler (IEEE 802.1Qbv). The translators of the user plane are in charge of holding the packet until it must be transmitted, and they are also in charge of synchronizing the 5G network with the TSN network.

In 5G systems three translators are considered: Network-Side TSN Translator (NW-TT) and Device-Side TSN Translator (DS-TT) in the user plane, and Application Function Translator (TSN AF) in the control plane. The DS-TT and NW-TT translators support a hold and forward mechanism to schedule traffic as defined in IEEE 802.1Q standard. For that purpose, the packets have to reach NW-TT or DS-TT ports before their scheduled transmission time. This functionality eliminates the latency jitter, causing outgoing traffic to be transmitted as planned. The NW-TT ports support connectivity to the TSN network, and the DS-TT ports are associated with the PDU session providing connectivity to the TSN network. On the other hand, the TSN AF is used to translate the 5GS protocols and to exchange information about the TSN bridge.

3.3.2.1 Communication between DS-TT and NW-TT

DS-TT and NW-TT translator are also in charge of synchronizing the 5G network with the TSN network [6]. More specifically, they must exchange gPTP messages to satisfy the requirements of the IEEE 802.1AS standard, which is the standard in charge of time synchronization in TSN. The IEEE 802.1AS procedures have already been described in section 3.1.4, and the integration in 5G is summarized as follows (see a more detailed explanation in section 3.3.4): after receiving a gPTP DL message, the NW-TT has to create a timestamp for message input (TSi) and add it to the message. After receiving a message in the user plane, the UE must forward it to the DS-TT. In this case, the DS-TT has to create an output timestamp (TSe) for each sync message. The DS-TT uses the TSi included in the message to calculate the processing time of the gPTP event within the corresponding 5G network domain (expressed in 5GS time). Finally, before sending the packet to the next TSN node, it has to remove the TSi from the message.

3.3.2.2 Communication between TSN AF and user plane translators (DS-TT and NW-TT)

There may also be communication between the TSN AF and the user plane translators (DS-TT and NW-TT) [7]. TSN AF communicates with the CNC to exchange information about the TSN bridge, and this involves having information related to the DS-TT and NW-TT Ethernet ports.

In a general way, the network and the UE can support the transfer of Ethernet specific information between AF and the DS-TT to manage the port used in the DS-TT for a PDU session. This information is included in PDU establishment and session modification messages.

The procedures that may appear differ depending on who initiates them: the network or the DS-TT. In the first case, the AF who requests it, does it to be aware, modify or to subscribe to be notified if the values of some port managements paraments change at the DS-TT Ethernet port. In the second case, it happens either when a change in the DS-TT Ethernet port occurs and there is an TSN AF that was subscribed to receive notifications about changes, or during the establishment of a PDU session.

Similarly, there is communication between AF and NW-TT. In this case, the communication is done together with N4 session level reporting procedures or with session managements policy association modification procedures.

On the other hand, one of the functionalities of the communication between the user plane translators and the TSN AF is the mapping of the QoS, where the different classes of TSN traffic are mapped to the different 5G QoS Identifier (5QI) indicators of the 5G QoS framework.

For a TSN bridge, QoS is related to traffic classes. Each traffic class is related to a priority level. Applying the fully centralized architecture, so that a TSN flow is transmitted over the 5G bridge, the 5G bridge communicates the characteristics of some nodes (for example, latency between nodes for different traffic classes) to publicize the service offered for the different classes of traffic. Traffic mapping consists of the following phases:

1. Reporting phase of bridge capabilities:
    a. The 5G bridge reports its capabilities to the CNC. This includes information about the bridge itself and existing ports. At this point only the PDU session has been established.
    b. The CNC uses this information to calculate routes and scheduling.
2. QoS communication phase:
    a. The CNC distributes the configuration to be fulfilled using the TSN AF, including the configuration of ports (scheduling parameters to comply with 802.1Qbv).
    b. Mapping of TSN qualities to 5G thanks to a mapping table of TSN QoS information to a 5G QoS profile. The 5G QoS profile identifies the 5G QoS characteristics with a 5QI and Allocation and Retention Priority (ARP) parameters, which define a Priority Level (PL) and whether the QoS flow can pre-empt another flow or if it can be pre-empted.
    c. The 5G system configures a QoS flow for TSN traffic based on the mapping table and the rules proposed by PCF.

3.3.3 Scheduler

In relation to the scheduler, the 5G system must emulate the IEEE 802.1 Qbv standard in order to respect the transmission of the scheduled packet and using the CNC to avoid collisions between TSN nodes. The mentioned standard is the core of TSN and is responsible of traffic scheduling.

The 3GPP system must support improvements related to TSN, such as the IEEE 802.1Qbv standard, for 5G-based Ethernet links with Ethernet-type PDU sessions. In addition to knowing when the message should be transmitted, 3GPP must define cyclic time bounds for DL and UL traffic. In addition to this, in 5G the existence of both hard-RT traffic and low priority traffic must be guaranteed through the use of a “time-aware scheduling”. Through this, lower priority traffic does not degrade the transmission of hard-RT traffic. In addition to this consideration, it is established that the information extracted from the Ethernet header created based on the IEEE 802.1Qbv standard must allow routing.

Finally, the 5G system must emulate the functionality of the IEEE 802.1Qbv standard if the application has strict requirements. The AF translator will receive from the TSN network the transmission time information of the TSN traffic classes. Based on this information, the translator in the UE (DS-TT) and the translator in the UPF (NW-TT) will be able to regulate the packet transmission accordingly.

3.3.4 Time synchronization

To support TSN time synchronization, the 5G system must also be integrated with the external network as a TSN bridge. The 5G system will be modelled as an entity compatible with 802.1AS, which is the standard in charge of the time synchronization in TSN. So, with the TSN synchronization, the entire E2E 5G system can be considered as a "time-aware system" IEEE 802.1AS. Only the TSN Translators at the edges of the 5G system (NW-TT and DS-TT) need to support this standard. The rest of the components that are within the 5G network, will be synchronized with the grand master (GM) clock of the 5G network.

Figure 13 shows the 5G and TSN clock distribution model through 5GS. Figure 13 also shows the two synchronization systems considered: synchronization in the 5G network and synchronization in the TSN domain. Also are shown the considered Master (M) and Slave (S) ports when the GM TSN is in the TSN working domain. The two synchronization processes can be considered independent of each other and the gNB only needs to synchronize with the GM clock of the 5G network.

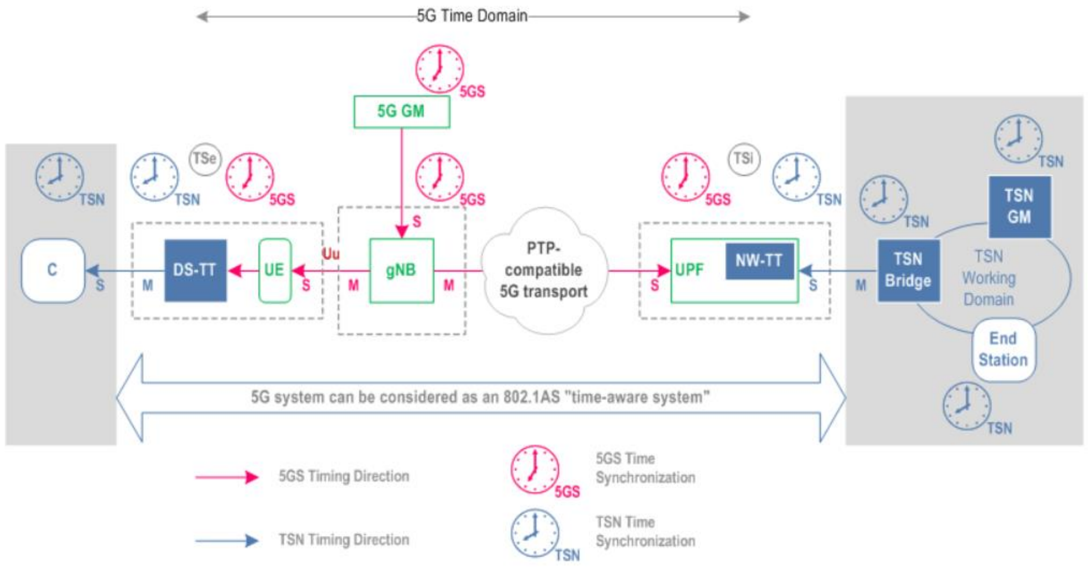

Figure 13: 5G system is modelled as IEEE 802.1AS-compliant time-aware system for supporting TSN time synchronization [8]

To provide TSN synchronization, 5G system calculates and adds the measured residence time between translator in the Correction Field (CF) of the TSN domain’s synchronization packets. Moreover, the internal clock of the 5G system must be shared by all the entities that make up the user plane in the 5G system.

3.3.4.1 Options for time synchronisation using TSN

Different proposals to accommodate TSN synchronization within the 5G cellular network are detailed in 3GPP technical report TR 23.734 [5] and several white papers [34], [35], [36]. All of them conclude that the ideal solution is the one in which the 5G system is conceived as a TSN bridge. The description of the proposal is detailed below.

In the case that there is only a single time domain, and the 5G system is conceived as a bridge, the 5G system is not altered and the impact in 5G is reduced to a minimum. As previously described in section 3.3.2, entities called translators are incorporated at the ends of the 5G system. As can be seen in Figure 14, the 5G network would be treated as a “distributed time-aware relay” where only the nodes at the ends of the network need to support the 802.1AS functionalities. In other words, 5G would be in charge of keeping its network synchronized, regardless of TSN.

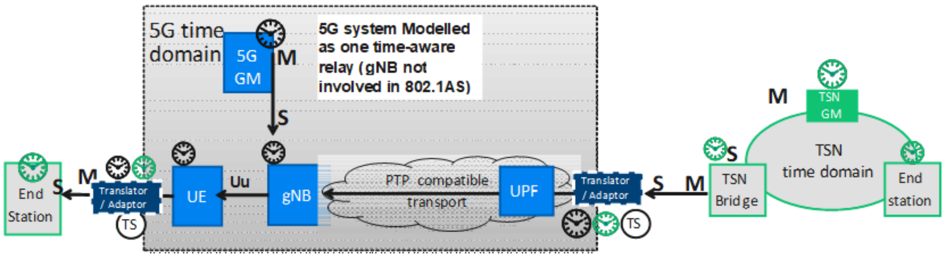

Figure 14: 5G system is modelled as one time-aware relay [5]

The internal 5G clock must keep the entities synchronized to be able to perform the gPTP timestamp correctly. The 5G system must perform the Best Master Clock Algorithm (BMCA) of the IEEE 802.1AS standard to be able to configure the status of the PTP ports and select the GrandMaster (GM) clock. The functions of the translator can be implemented independently or together with the network end entities, UPF/UE. In this way the time information related to the TSN network arrives from the UE to the TSN end devices. Moreover, with this architecture and thanks to the transport network that supports gPTP messages, the internal 5G clock must reach to the translators and to all the entities of the 5G system. The information from the internal clock of the 5G system can reach the UE thanks to signalling (SIB / RRC), while the time information (gPTP messages) can be transported from the UPF to the UE as data packets.

To support multiple time domains, the parameter “domainNumber” is introduced into the exchanged packets to distinguish time domains within the same translator. It should be noted that for the 5G system the existence of a single time domain or multiple time domains is transparent with the solution described in section 3.3.4.1. As previously described in section 3.3.2, the translator at UPF (NW-TT) includes a timestamp along with the time information and this message is transmitted to all UEs in that user plane (within each of the PDU sessions). Once the message reaches the UE translator (DS-TT), it calculates thanks to another timestamp that it creates the residence time of the message within the 5G system. This is included in the message that it is send to TSN end stations using the “correctionField” of the TSN domain’s synchronization packets. TSN end stations will select the correct TSN information based on the "domainNumber" as seen in Figure 15.

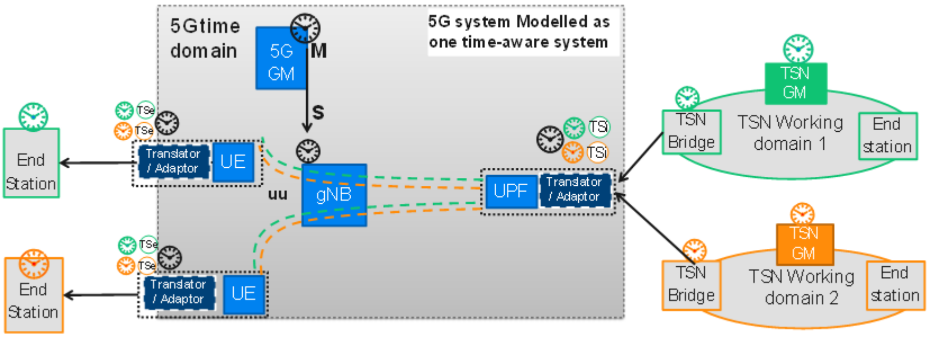

Figure 15: Supporting multiple TSN working domains [5]

When considering a system with multiple time domains, it must be taken into account that the ideal solution is that the 5G clock works as a transparent clock. That is, the gPTP message simply crosses the 5G system and the residence time is added in the “correctionField” parameter, without the need to synchronize with any external clock.

3.3.4.2 DL Time Synchronization for TSN

Both UPF and NW-TT can obtain the 5G clock thanks to a PTP compliant transport network with mechanisms that are not in the scope of 3GPP. On the contrary, the UE can be aware of the 5G clock thanks to the time signalling related to the frames, and then make it available to the DS-TT. All the exchanged gPTP messages are sent in flows whose QoS must allow the requirements of 802.1AS to be met.

On the other hand, the TSN clock must be distributed as defined in IEEE 802.1AS standard. After receiving a gPTP DL message, the NW-TT creates a timestamp (TSi) for each gPTP event and uses the accumulated rateRatio included in the message to calculate the delay introduced. After that the NW-TT calculates the new rateRadio (accumulated by 5G system), modifies the gPTP message adding the delay that it just calculated, adds the new rateRadio, and adds the TSi that it has created. After that, the gPTP message goes through the UPF and the UPF forwarded it by all the PDU sessions that end in that UPF. These PDU sessions had been established by the UE towards the TSN network.

The UE after that receives the gPTP message and forwards it to the DS-TT. The DS-TT creates another timestamp (TSe) for each gPTP message. The difference between TSi and TSe is the time that the message has elapsed within the 5G system (expressed in 5G time). The DS-TT uses the rateRatio parameter, that is in the message, to convert the time that the message has elapsed within the 5G system to TSN time and modifies the message that it sends to the TSN node. In this last message, the DS-TT has to remove the T-Si introduced by the NW-TT and it has to add the time that the message has elapsed within the 5G system (expressed in TSN time).

This procedure is repeated on all TSN domains that exist between a DS-TT and a NW-TT. Each domain works with its own gPTP messages, since the Ethernet messages that support it carry a specific domainNumber field that indicates which domain they refer to.

3.3.4.3 UL Time Synchronization for TSN

In TR 23.700-20 [4], a similar operations defined for DL TSN Time Synchronization is proposed for the UL TSN Time Synchronization. In this case, the TSN GrandMaster (GM) attached to the UE will generate an UL gPTP message. The rest of the 5G system would do the same functions as in DL time synchronization but changing the direction of the communication. That is, first the DS-TT will perform the same operations for the received UL gPTP messages as NW-TT performs for the DL gPTP messages. Second, the modified UL gPTP messages will be forwarded via the user-plane until the target UPFs and after the NW-TT will perform the same operations for the received UL gPTP message as DS-TT performs for the DL gPTP messages. As last step, the UL gPTP message will be forwarded to the TSN end station by the NW-TT.

The main difference between the DL and UL time synchronization is that the UL gPTP messages are also required by the TSN end stations behind the other UEs. For that, the UPF will forward the UL gPTP messages transparently to other no GM TSN end stations and following the operation defined in section 3.3.4.1 and 3.3.4.2. The followed procedure for UL time synchronization is shown in Figure 17 and Figure 18. The first two steps of this procedure are related to BMCA procedure. In contrast, the steps 4 to 8 are related to the operation described in section 3.3.4.1 and 3.3.4.2 which include the creation of input and output timestamp (TSi and TSe).

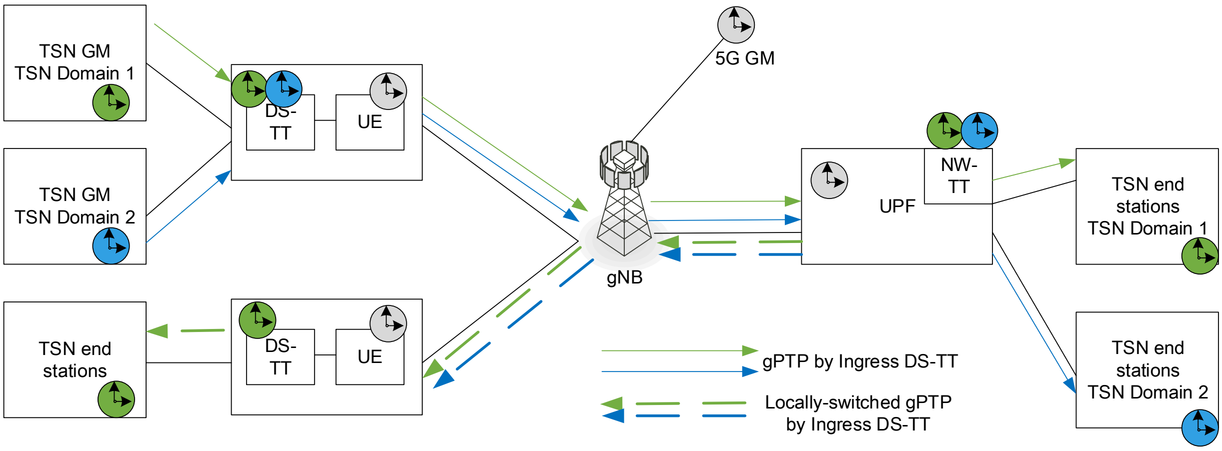

Figure 16: The distribution of UL Time Synchronization Information with the same UPF [4]

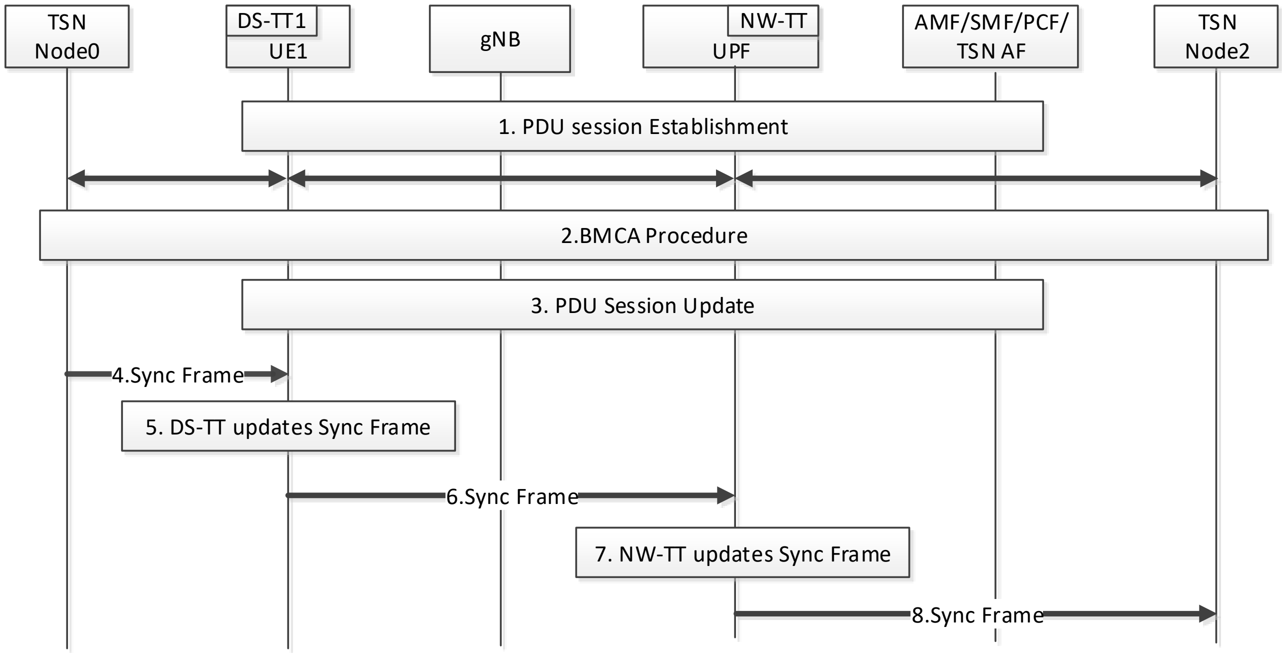

Figure 17: Procedure of UL time synchronization for TSN end stations behind 5G System [4]

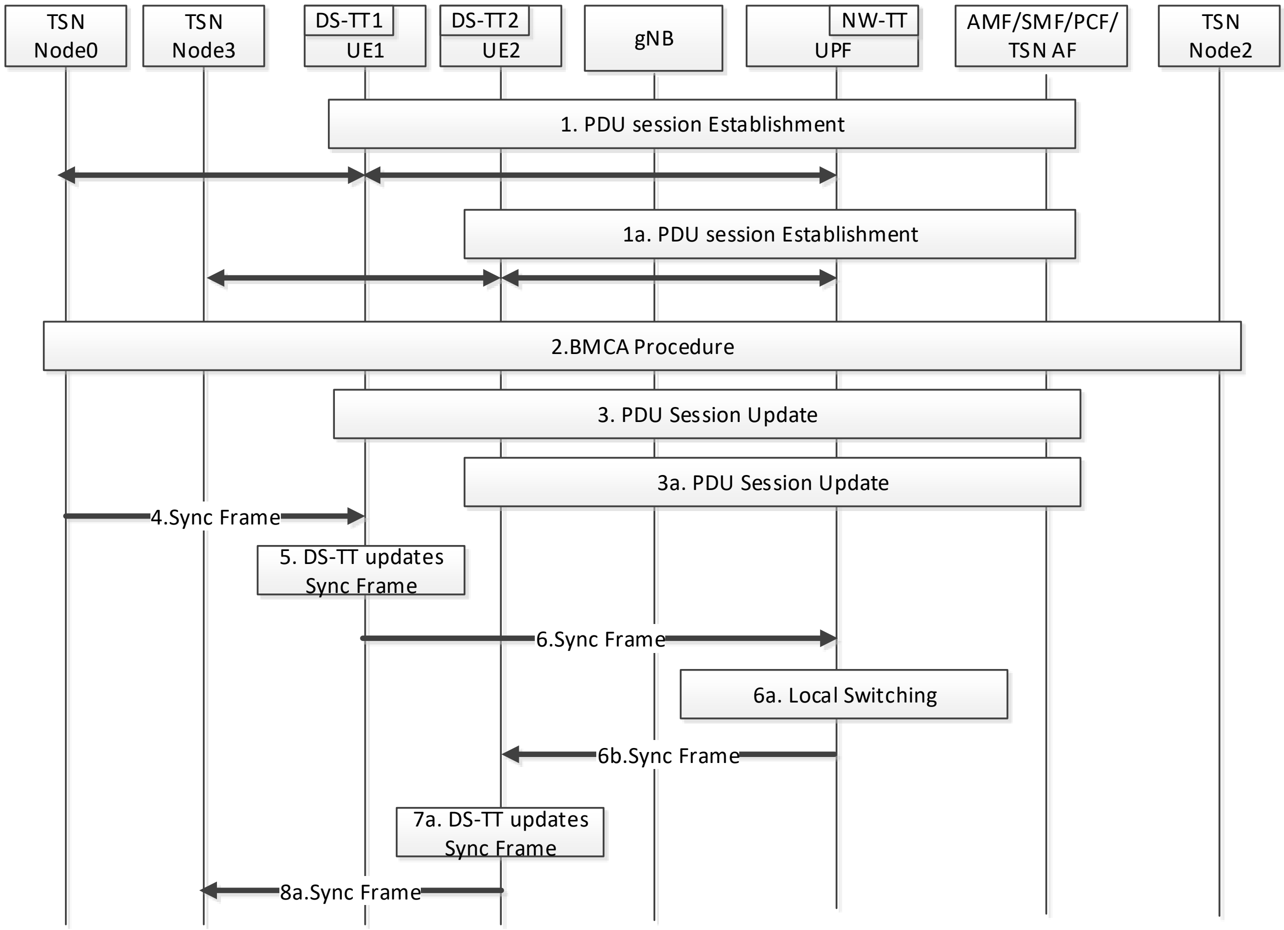

Figure 18: Procedure of UL time synchronization for TSN end stations behind other UEs [4]

3.4 AETBN Requirements

The requirements for the Adapted-ETBN device of the WLTB are detailed In Safe4RAIL-2 deliverable D2.1 “Requirements of LTE Equipment and ETBNs for wireless TCMS”. Some of these requirements are related to TSN, and they have been analyzed further in this report. This analysis is included in Annex 7.1. As can be observed, some of the requirements still need further analysis and alignment. This would require a separate low-TRL research line, as well as the availability of radio technologies with TSN capabilities as appointed in the previous section. Upcoming Shift2Rail initiatives are focused on increasing the Technology Readiness Level (TRL) of the currently proposed WLTB solution. Therefore, the analysis performed in this chapter represents a first assessment for the extension of the Drive-by-Data concept to the WLTB, and points out the issues that should be considered if this activity is continued in the future.

Chapter 4 Applicability of 4G and 5G Technology on Wireless TCMS

In this chapter an analysis has been made on how 4G, 4G-V2X, 5G and 5G-V2X technologies can meet the traffic requirements of CONNECTA-2 WLTB and WLCN. These requirements come from CONNECTA D3.1, and they are summarized in Table 6.

4.1 Network Topologies

Two network topologies have been considered for this analysis: infrastructure-based for 4G/5G, and Device to Device for 4G-V2X/5G-V2X.

4.1.1 *Infrastructure-Based*

Figure 19 shows the topology of an infrastructure-based WLTB. This network operates as a star topology, where a eNodeB/gNodeB placed in the central consist acts as a gateway managing the traffic which flows through the backbone. A maximum of 63 consists is considered. Hence, transmissions can be unicast or multicast with a maximum of 63 destination addresses.

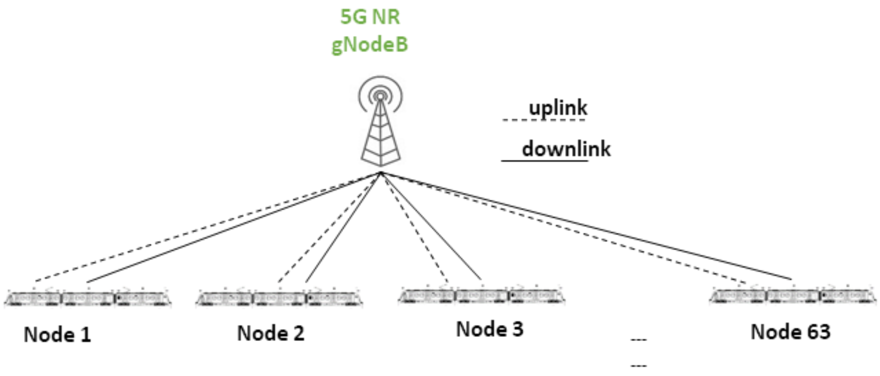

Figure 19. Infrastructure-based WLTB topology

The communication inside a consist (WLCN) also makes use of a star topology (see Figure 20). In this setup, a femtocell (i.e. a base station with lower nominal power) is needed per car, acting as a central node that manages the traffic flow between Wireless End Devices (WEDs) See Annex 7.3 for 5G femtocells range analysis. A maximum of 30 WEDs is considered per car.

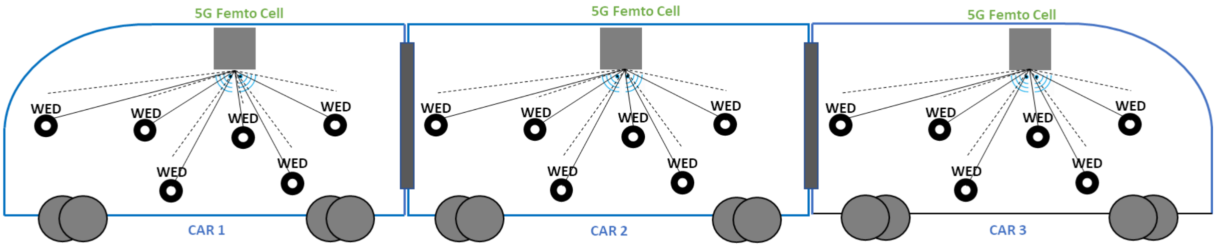

Figure 20. Infrastructure-based WLCN topology

4.1.2 Device to Device

For the Backbone link there are a maximum of 32 vehicles per consist, 63 consist per train and 2 intermediate hops are needed to reach the maximum allowed train length of 860m (see Figure 21).

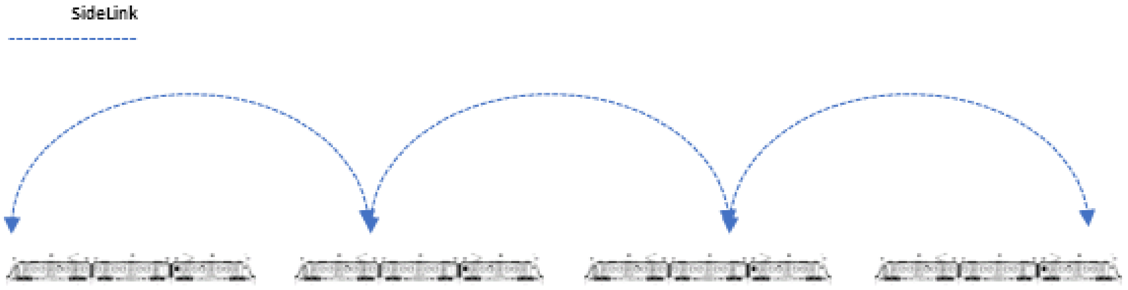

Figure 21. Device-to-device WLTB topology

For the consist, the femtocell which acted as central node in infrastructure mode is omitted in the case of Device-to-Device topology (see Figure 22).

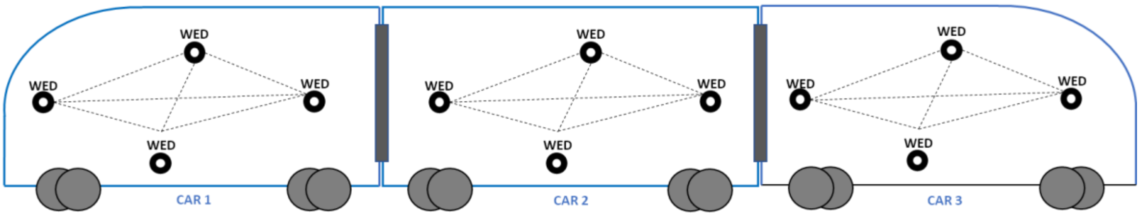

Figure 22. Device-to-device WLCN topology

4.2 4G

Different analyses have been performed to assess the feasibility of 4G technology for WTCMS. First, solutions provided by 3GPP to similar industrial use cases have been analyzed; afterwards, a resource-grid analysis has been done.

4.2.1 Use Case Analysis

Use case analysis relates the CONNECTA-2 WTCMS requirements with the features specified in 3GPP documents for similar traffics. The goal is to identify whether these requirements are reachable or not by comparing them to the limits aimed in the technical specifications/reports. This analysis can be seen in Table 6 for 4G and 4G-V2X technology. It can be observed that for the most demanding cases neither data rate nor cycle time are satisfied by comparing to the requirements specified by conventional industrial control traffic in [9]. Also, this analysis points out that the data rate required by video streaming traffic in WLCN case cannot be achieved. All in all, 4G technology struggles to accomplish the requirements presented by the most demanding traffics.

WLTB / WLCN																		
Traffic Type	**Max. Data Size (bytes)**	**Max. Bit Rate**	**Min. Cycle Time**	**Max. Latency**	**Jitter**	**4G**							**4G-V2X**					
PD (Time Sensitive)	1432	100 Mbps	1 ms	16 ms / 4 ms	±1%	v	x	x	v	-	[9, Sec. 7.3]	The approach followed to complete this compliance table has considered the traffic requirements published among different use of cases in 3GPP specifications and reports (TS, TR). Among all the published traffics, those which present more similarities have been compared with the requirements & traffics here described. The table expresses the compliance or not including the reference to the TS&TR where the specific traffic is detailed.	x	x	x	x/x	-	Compliance or not compliance of the requirements demanded is decided according to the 3GPP technical specification TS 22 185, which specifies the requirements demanded for 4G-V2X in terms of latency/reliability, frequency, range, speed, and security. Hence, from TS 22 185, the maximum performance for 4G-V2X can be considered as follow: • Max Packet Size: 1200 bytes [R - 5 . 2. 2 - 002] • Max Data Rate: 96 Kbps [R - 5 . 2. 3- 001] • Max Latency: 20 msec [R - 5 . 2. 1 - 002] • Max Time cycle: 100 msec [R - 5.2.1 - 001]
PD (Normal)	1432	100 Mbps	10 ms / 1 ms	32 ms / 8 ms	±50%	v	x	x	v	-	[9, Sec. 7.3]		x	x	x / x	x/x	-	
MD (Normal)	65388	10 Mbps	N/A	500 ms / 250 ms	Not relevant	-	v	-	v	-	[9, Sec. 7.7]		x	x	-	v/v	-	
SD	Not relevant	10 Mbps	50 ms	32 ms / 8 ms	±50%	-	v	-	v	-	[9, Sec. 5.2]/ [9, Sec. 7.7]		-	x	v	v/x	-	
Streaming (Audio)	N/A	3.2 Mbps / 2 Mbps	N/A	100 ms	≤80 ms	-	v	-	v	-	[10, Sec. 6.1.7.2] & [11]		-	x/x	-	v	-	
Streaming (Video)	N/A	256 Mbps / 512 Mbps	N/A	100 ms	≤80 ms	-	v/x	-	v	-	[10, Sec. 6.1.7.2] & [11]/[9, Sec. 7.5]		-	x/x	-	v	-	
Best Effort	4 GB	≥ 10 Mbps	N/A	Not Relevant	Not relevant	-	v	-	-	-	[9, p. 7.7]		x	x	-	-	-	
TOTAL	-	**489.2 Mbps / 744 Mbps**	**-**	-	-													

PD: Process Data
MD: Message Data
SD: Supervisory Data
N/A: Not Applicable

v: requirement met
x: requirement not met
-: information not available

Table 6. 4G & 4G-V2X use cases requirement analysis

4.2.2 Resource Grid Analysis

In a second approach, the LTE resource grid design is analysed. This second analysis aims at concluding if the traffic defined by CONNECTA-2 could be placed within a custom resource grid of 4G. In order to do that, the demanded traffic, divided into TCMS (Train Control and Monitoring System) and OMTS (On Board Multimedia and Telematic Services), and the real 4G capacity must be matched and evaluated.

Table 7 and Table 8 detail the packet size transmitted in each 4G subframe. Annex 7.2 details the analysis and procedures carried out to obtain these results, where a worst-case scenario has been considered for the traffic generation. As a first approach, the same data size values can be assumed for WLTB and WLCN[2].

TCMS packet size (Bits per ms)				
Process Data		**Message Data**	**Supervisory Data**	**TOTAL**
Time Sensitive	***Normal***			
11536	1226	10080	320	**23162**

Table 7 TCMS packet size

OMTS packet size (Bits per ms)			
Streaming		**Best Effort**	**TOTAL**
Audio	**Video**		
3280	256080	10080	**269440**

Table 8 OMTS packet size

Regarding the capacity of 4G, considering that the maximum bits which can be embedded within a subframe is delimited by the maximum REs available, a gross calculation indicates that the maximum REs available in one subframe of 1 msec are 16800 (14 symbols per subframe x 12 subcarriers x 100 RB per 20 MHz of bandwidth), which implies 50kbits per subframe (half for uplink and half for downlink) as maximum, without subtracting REs used for signalling and reference, and setting a modulation order of 6 and a coding rate of 0.5. As it can be observed in Table 7 and Table 8, one node transmitting a packet requires 23Kbits per subframe (TCMS) or 270kbits per subframe (OMTS). Therefore, we can confirm that 4G is not a suitable technology for WLTB or WLCN.

4.2.3 Latency

Moreover, attending to latency that is achievable in 4G, frame structure and fixed numerology are big constraints. Frame structure in LTE goes as follows: frame divided in 10 subframes, each of which is divided in two slots, including 6 or 7 OFDM slots with a subcarrier spacing of 15 kHz, being 1ms and 0.5ms the subframe and slot duration, respectively.

A certain number of physical resource blocks are allocated to a UE. Since the time unit for the physical resource block is the slot, a DL transmission is longer than 0,5ms. Considering the retransmission delay this number enlarges considerably. Hybrid Automatic Request (HARQ) round trip timer specifies the number of subframes before a retransmission can take place (Figure 23). For LTE advanced, it is assumed a processing time of 3ms for BS and UE and

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[2] It must be noted that in a consist network there are also devices such as sensors who will have much lower traffic requirements.

since retransmissions are acknowledged, latency goes over 10ms. In industrial environments 4G have been tested showing latencies around 40ms [16].

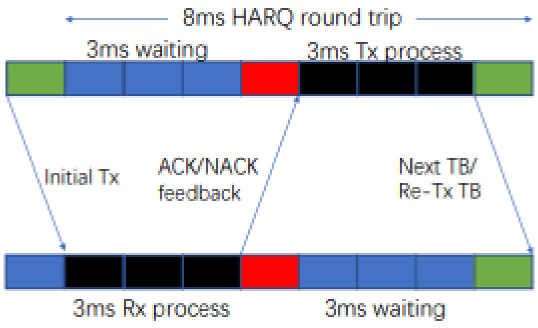


Figure 23 LTE HARQ process. [17]

4.3 4G V2X

Following the same approach as with 4G, different analyses are performed to assess the feasibility of 4G-V2X technology for WTCMS.

4.3.1 Use Case Analysis

The technical specification TS 22.185 [22] has been considered for this analysis, where the requirements compiled by 3GPP for V2X services are identified. It can be observed in Table 6 that WTLB and WLCN requirements cannot be achieved by 4G-V2X technology.

4.3.2 Resource Grid Analysis

A LTE-V2X grid design is analysed in order to conclude if the traffic requirements demanded by WLTB and WLCN can be placed within a custom 4G-V2X grid. 4G-V2X (LTE Mode 4) works without infrastructure (i.e. it has no eNodeB), so configuration of resources and scheduling are carried out by UEs (SPS: Semi Persistent Scheduler). In time domain, the resource grid is similar to other modes with a subframe of 1 ms; however, out of 14 symbols, only 9 can be used for data as 4 of them are reserved for Demodulation Reference Signals (DMRS) and the last one is a guard symbol which can be used, for instance, for AGC (Automatic Gain Control) processes. Moreover, modulation orders allowed are QPSK (2 bits per symbol transmitted) and 16-QAM (4 bits per symbol transmitted).

Apart from that, the key characteristic of this configuration mode is in the frequency domain, where resource allocation is in a subchannel granularity. RBs (Resource Blocks) are grouped into subchannels composed of control information (mapped in PSCCH: Physical SideLink Control Channel) and user data (mapped in PSSCH: Physical SideLink Shared Channel). The total bandwidth available is split into subchannels and each subchannel contains a number of RBs (Resource Block). Subchannel size and number of subchannels allowed are defined and specified in 3GPP standards [23].

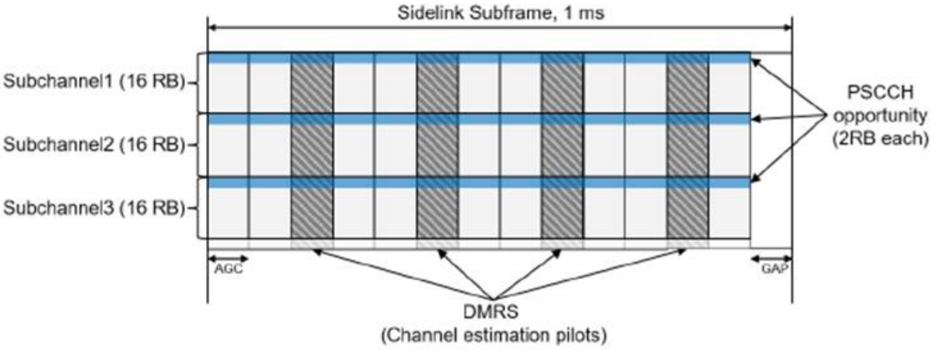


Figure 24 4G – V2X subframe [23]

A gross calculation indicates that the maximum REs available in one subframe of 1 msec are 10800 (9 symbols per subframe for data x 12 subcarriers x 100 RB per 20 MHz of BW), which implies 21kbits for SideLink per subframe as maximum, without subtracting REs used for signalling and reference and setting a modulation order of 4 and a coding rate of 0.5. It can be observed from Table 7 and Table 8 that a minimum packet size of 23kbits is required per subframe, which is too big to be embedded within the custom resource grid detailed before. Therefore, we can conclude that 4G-V2X is not a suitable technology to cover the required traffic for WLTB or WLCN.

4.3.3 Latency

In 4G-V2X latency is determined by scheduler performance and processing time. As there is no eNodeB in 4G-V2X, scheduling is carried out by UEs using LBT (Listening Before Talk) algorithms. Hence, scheduling timing is divided in Sensing Window, which stores the activity sensed during the last 1000 subframes (1 sec), and Selection Window with a configurable size (between 20 and 100 mseg), which obtains the resources which are free to be used to transmit user data after a purging process [23].

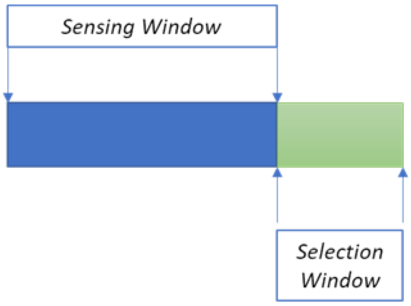


Figure 25 4G – V2X latency analysis

Once resources are assigned to a UE, they are booked for a time (also variable), after which the UE must start the reservation process again. This is a process which takes too much time, with a worst-case value of 20 ms and average value of 10 ms (selection window), plus airtime and codification/de-codification processes (4 ms). Therefore, latency requirements cannot be fully accomplished. Furthermore, this is a not deterministic process in 4G-V2X.

4.4 5G

A similar study as the one described in Section 4.2 has been performed for 5G, first attending to the requirements specified by the standard itself, and then designing a resource grid for evaluating the feasibility of occupying it with the desired traffic. A latency analysis is also presented.

4.4.1 Use Case Analysis

The use case analysis for 5G technology, detailed in Table 9, concludes that almost every WLTB and WLCN requirement seems achievable considering the information provided by the technical specifications in the standard. Only in the Process Data traffic, which can be related to the requirements specified for mobile control panels, robots and differential protection presented in [12], the jitter requirement is unsatisfied.

WLTB / WLCN																		
Traffic Type	**Max. Data Size (bytes)**	**Max. Bit Rate**	**Min. Cycle Time**	**Max. Latency**	**Jitter**	**5G**							**5G – V2X**					
PD (Time Sensitive)	1432	100 Mbps	1 ms	16 ms / 4 ms	±1%	v	-	v	v	x	[12, Sec. 8.1.2]	The approach followed to complete this compliance table has considered the traffic requirements published among different use of cases in 3GPP specifications and reports (TS, TR).. Among all the published traffics, those which present more similarities have been compared with the requirements & traffics here described. The table expresses the compliance or not including the reference to the TS&TR where the specific traffic is detailed.	x	x	x	v/x	-	Compliance or not compliance decision of the requirements demanded is decided according to the 3GPP technical specification TS 22 186, which specifies the enhancements for V2X in 3GPP systems (i.e EPS, 5G). This technical specification specifies service requirements to enhance 3GPP support for V2X in several areas. Out of all scenarios available, *Vehicles Platooning* is selected because being considered the best approximation to the WLTB. Depending on the communication scenario and automation degree, platooning scenario is divided into lowest, low, Highest or High degree of automation. Considering highest degree of automation the most suitable, the maximum performance for 5G-V2X can be considered as follow [R - 5 . 2. 2 - 006]: • Max Packet Size: 1200 bytes • Max Data Rate: 282 kbps • Max Latency: 10 msec • Max Time cycle: 34
PD (Normal)	1432	100 Mbps	10 ms / 1 ms	32 ms / 8 ms	±50%	v	-	v	v	v	[12, Sec. 8.1.2]		x	x	x/x	v/x	-	
MD (Normal)	65388	10 Mbps	N/A	500 ms / 250 ms	Not relevant	-	v	-	v	-	[13, Sec. 7.6.1]		x	x	-	v/v	-	
SD	Not relevant	10 Mbps	50 ms	32 ms / 8 ms	±50%	-	-	v	v	-	[14, Sec. 5.2]		-	x	v	v/x	-	
Streaming (Audio)	N/A	3.2 Mbps / 2 Mbps	N/A	100 ms	≤80 ms	-	v	-	v	-	[15, Sec. 5.2.2]		-	x/x	-	v	-	
Streaming (Video)	N/A	256 Mbps / 512 Mbps	N/A	100 ms	≤80 ms	-	v	-	v	-	[12, Sec. 81.5]		-	x/x	-	v	-	
Best Effort	4 GB	≥ 10 Mbps	N/A	Not Relevant	Not relevant	-	v	-	-	-	[13, Sec. 7.1]		x	x		-	-	
TOTAL	-	**489.2 Mbps / 744 Mbps**	-	-	-													

PD: Process Data
MD: Message Data
SD: Supervisory Data
N/A: Not Applicable

v: requirement met
x: requirement not met
-: information not available

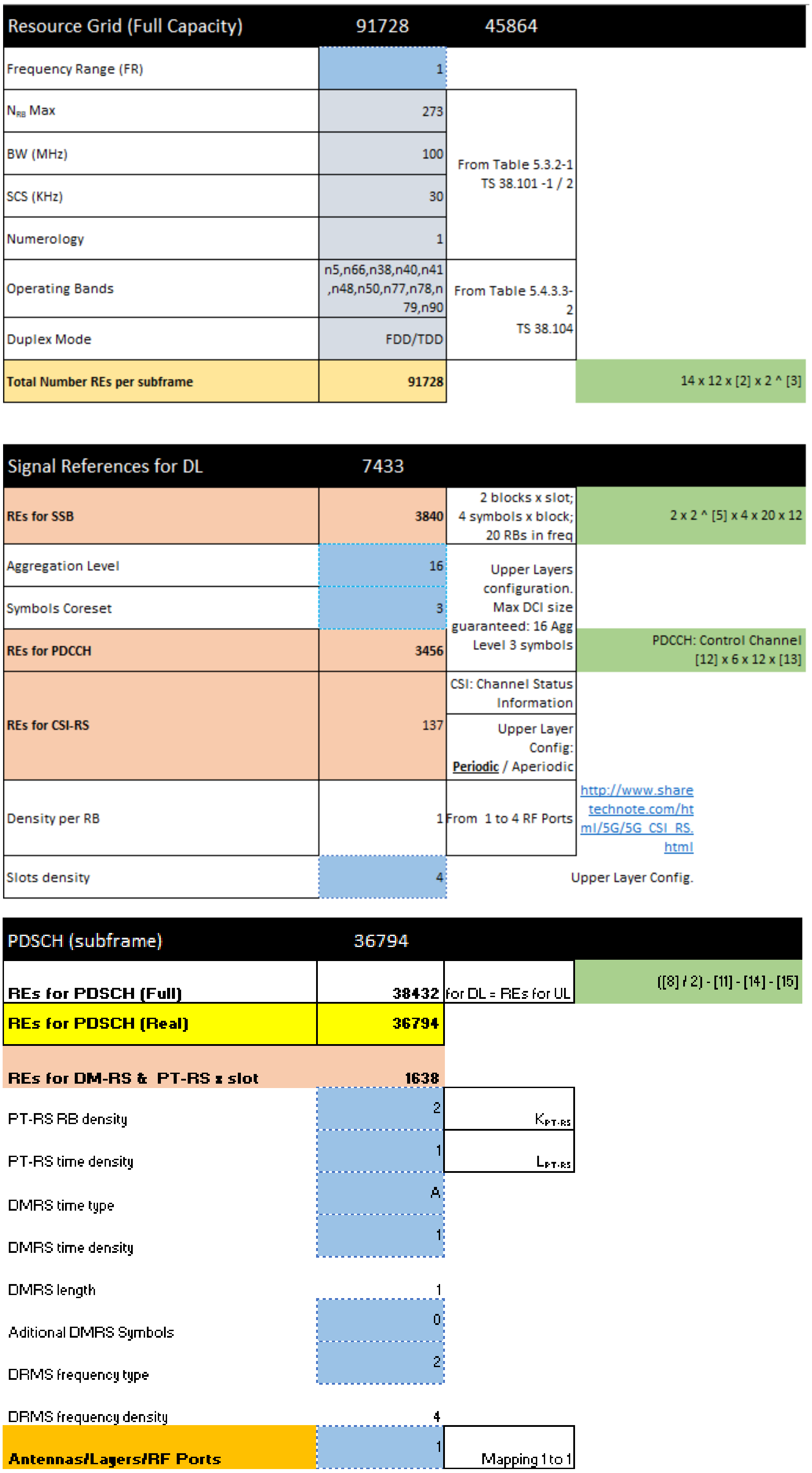
Table 9. 5G & 5G-V2X use cases requirement analysis

4.4.2 Resource grid analysis

In FR1 (Frequency Range 1, below 7GHz for 400 MHz of BW) there are in total 91728 REs (273 RBs [26] x 2^1 slots x 14 symbols x 12 subcarriers), which implies 275kbits per subframe for Uplink and Downlink, and 354816 REs in FR2 (Frequency Range 2, above 24 GHz for 400 MHz of BW) (264 [26] x 2^3 slots x 14 symbols x 12 subcarriers) or 1Mbits per subframe for Uplink and Downlink. This analysis is completed considering the resources which must be discarded because of being reserved for channel control and reference signals. In order to do this analysis, and due to the significant variability of the 5G parameters, several assumptions have been made:

1. It is assumed that the whole bandwidth is available (400 MHz), half for Uplink and half for Downlink (i.e symmetric resource allocation).
2. The most restrictive configuration is adopted regarding the amount of resources occupied by control channels and signals. For this, it is assumed that the periodic information (PRACH: Physical Random Access Channel, SRS: Sounding Reference Signal, CSI-RS: Channel Status Information - Reference Signal in uplink, SSB: Synchronization Signal Block and CSI-RS in downlink) is transmitted in the same subframe as the data (PUSCH: Physical Uplink Shared Channel in uplink, PDSCH: Physical Downlink Shared Channel in downlink).
3. It is considered that the streams from codewords codifications are directly mapped into RF ports and physical antennas, allowing spatial multiplexing.

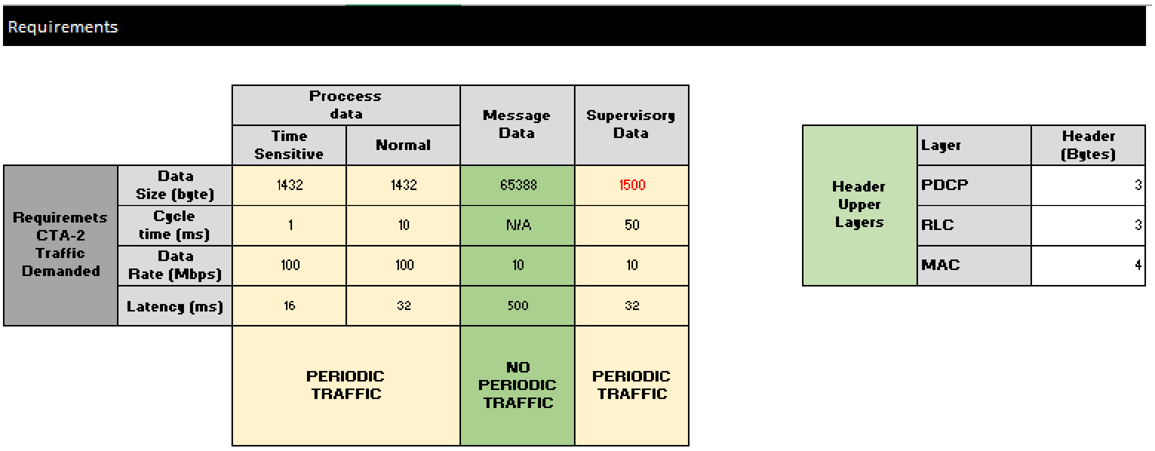
Based on the previous assumptions, out of all REs obtained in gross calculations (91728 for FR1 and 354816 for FR2) those reserved for control channels and signals are subtracted. However, this procedure is not trivial as it has many dependencies on upper layer configurations. To overcome this issue, a dynamic excel sheet has been programmed where final PDSCH and PUSCH capacities change depending on these parameters (see snapshot in Table 10). As it was remarked in the previous points, the results presented are under the assumption of being the most restrictive configuration in terms of capacity.



Resource Grid (Full Capacity)	91728	45864	
Frequency Range (FR)	1		
N_{RB} Max	273	From Table 5.3.2-1 TS 38.101 -1 / 2	
BW (MHz)	100		
SCS (KHz)	30		
Numerology	1		
Operating Bands	n5,n66,n38,n40,n41,n48,n50,n77,n78,n79,n90	From Table 5.4.3.3-2 TS 38.104	
Duplex Mode	FDD/TDD		
Total Number REs per subframe	**91728**		14 x 12 x [2] x 2 ^ [3]

Signal References for DL	7433		
REs for SSB	**3840**	2 blocks x slot; 4 symbols x block; 20 RBs in freq	2 x 2 ^ [5] x 4 x 20 x 12
Aggregation Level	16	Upper Layers configuration. Max DCI size guaranteed: 16 Agg Level 3 symbols	
Symbols Coreset	3		
REs for PDCCH	**3456**		PDCCH: Control Channel [12] x 6 x 12 x [13]
REs for CSI-RS	137	CSI: Channel Status Information Upper Layer Config: Periodic / Aperiodic	
Density per RB	1	From 1 to 4 RF Ports	http://www.sharetechnote.com/html/5G/5G_CSI_RS.html
Slots density	4		Upper Layer Config.

PDSCH (subframe)	36794		
REs for PDSCH (Full)	**38432**	for DL = REs for UL	([8] / 2) - [11] - [14] - [15]
REs for PDSCH (Real)	**36794**		
REs for DM-RS & PT-RS x slot	**1638**		
PT-RS RB density	2	$K_{PT\text{-}RS}$	
PT-RS time density	1	$L_{PT\text{-}RS}$	
DMRS time type	A		
DMRS time density	1		
DMRS length	1		
Aditional DMRS Symbols	0		
DRMS frequency type	2		
DRMS frequency density	4		
Antennas/Layers/RF Ports	1	Mapping 1 to 1	



Requirements

		Process data		Message Data	Supervisory Data
		Time Sensitive	Normal		
Requiremets CTA-2 Traffic Demanded	Data Size (byte)	1432	1432	65388	1500
	Cycle time (ms)	1	10	N/A	50
	Data Rate (Mbps)	100	100	10	10
	Latency (ms)	16	32	500	32
		PERIODIC TRAFFIC		NO PERIODIC TRAFFIC	PERIODIC TRAFFIC

	Layer	Header (Bytes)
Header Upper Layers	PDCP	3
	RLC	3
	MAC	4

Table 10. Dynamic Excel sheet snapshot

Finally, once REs available for transmitting data are obtained, depending on the MCS (Modulation Coding Scheme) and spatial configuration (number of TX antennas and band of transmission: FR1 or FR2), the maximum capacity offered (Rb in Mbps) varies. According to [26], 28 different MCS Index which can be selected during the codification process. In this case, four of them have been selected as representative between 0 and 28 (MCS=0, 10, 20 and 28).

It must be noted that the worst-case traffic demanded for WLTB and WLCN is the same even though the cycle time is different in some traffics of both domains. Therefore, the only difference between consist and backbone are presented in the total final traffic demanded due to the number of nodes. In that sense, in the WLTB the maximum size is limited to 63 nodes, while it is limited to 30 nodes per car in the WLCN.

4.4.2.1 TCMS Traffic Results

Once 5G resource grid customization process is presented (see 4.4.2), depending on the MCS index and spatial multiplexing (i.e: number of transmission antennas and frequency range) the maximum capacity (Mbps) offered by 5G is calculated. It has been summarized in Table 11.

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

Table 11 Maximum capacity (Mbps) - TCMS

If maximum capacity offered by each configuration (FR – Antennas) and TCMS traffic demanded are plotted in the same graph (according to the four MCS Index analysed), Figure 21, Figure 22, Figure 23, Figure 24 are obtained for Uplink and Figure 25, Figure 26, Figure 27, Figure 28 for Downlink. These graphs indicate the required Uplink and Downlink 5G bit rates according to the traffic presented in Table 7 for each MCS scheme and number of nodes (red curve). Therefore, they must be interpreted as follow: on the one hand, blue and green lines fix the maximum capacity that the customized 5G resource grid is able to cover in a specific scenario: FRx (Frequency Range) – y ANT. On the other hand, red curve describes the capacity demanded when the number of nodes is increased. The cross-point among these curves set the maximum number of nodes for each configuration.

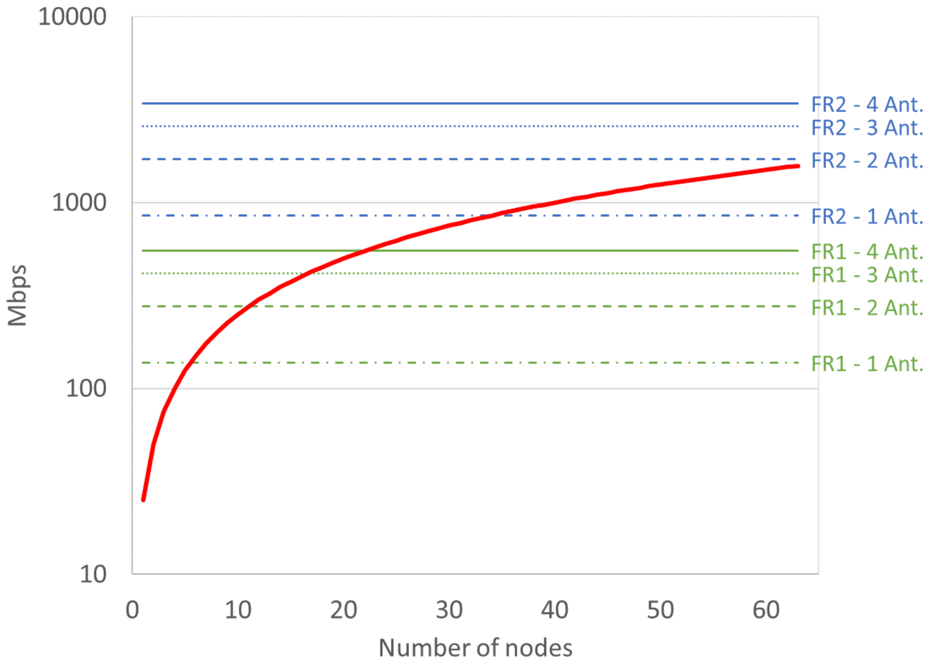


Figure 26 MCS 28 Uplink - TCMS

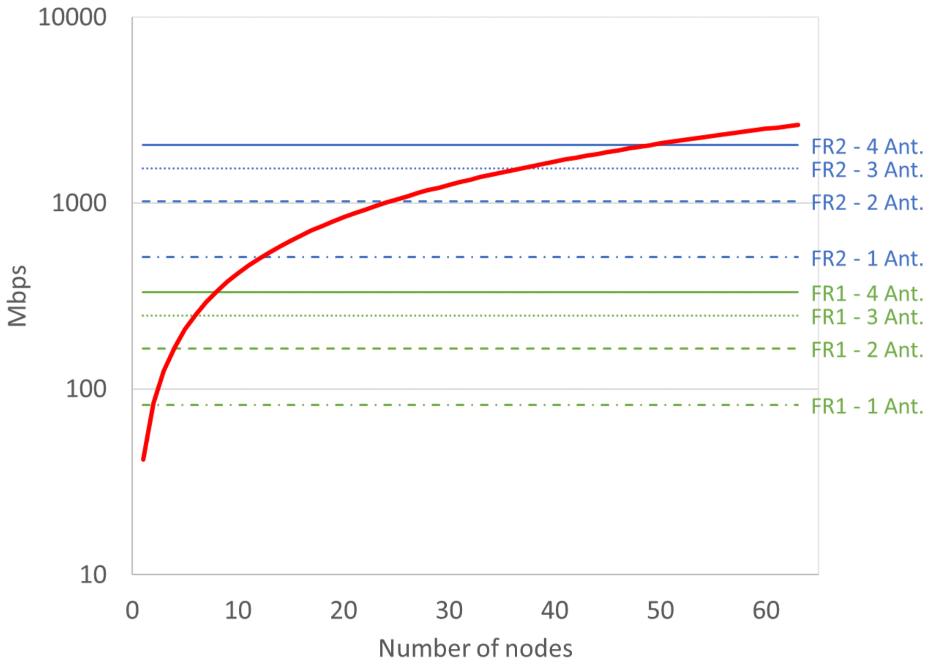


Figure 27 MCS 20 Uplink - TCMS

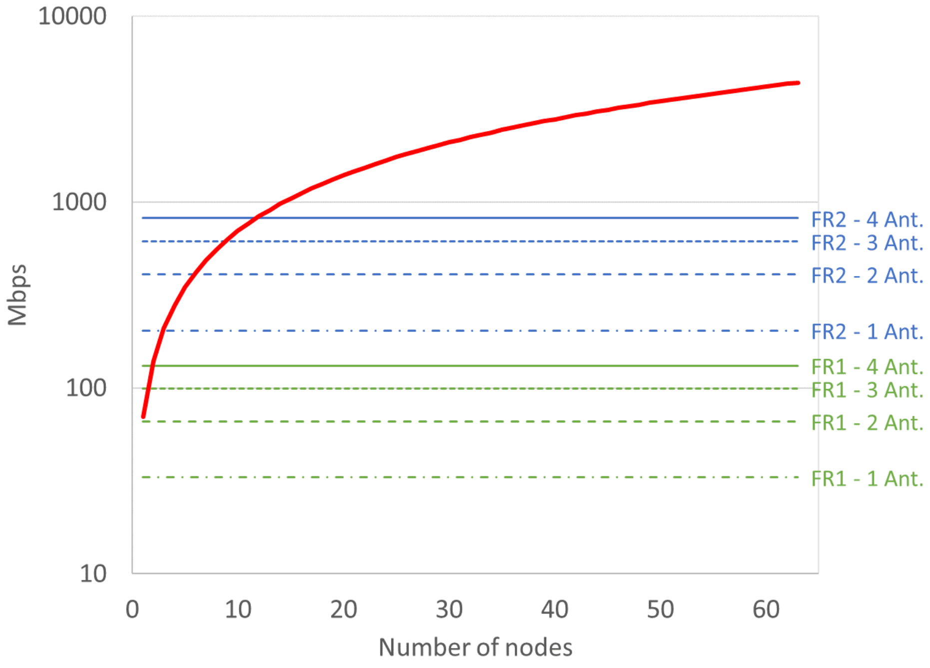


Figure 28 MCS 10 Uplink - TCMS

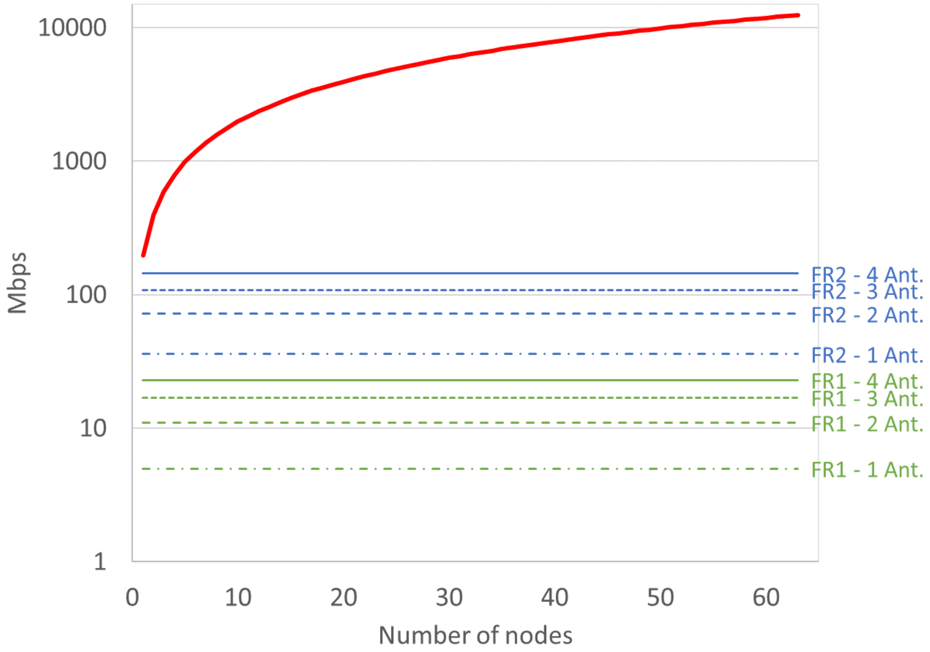


Figure 29 MCS 0 Uplink - TCMS

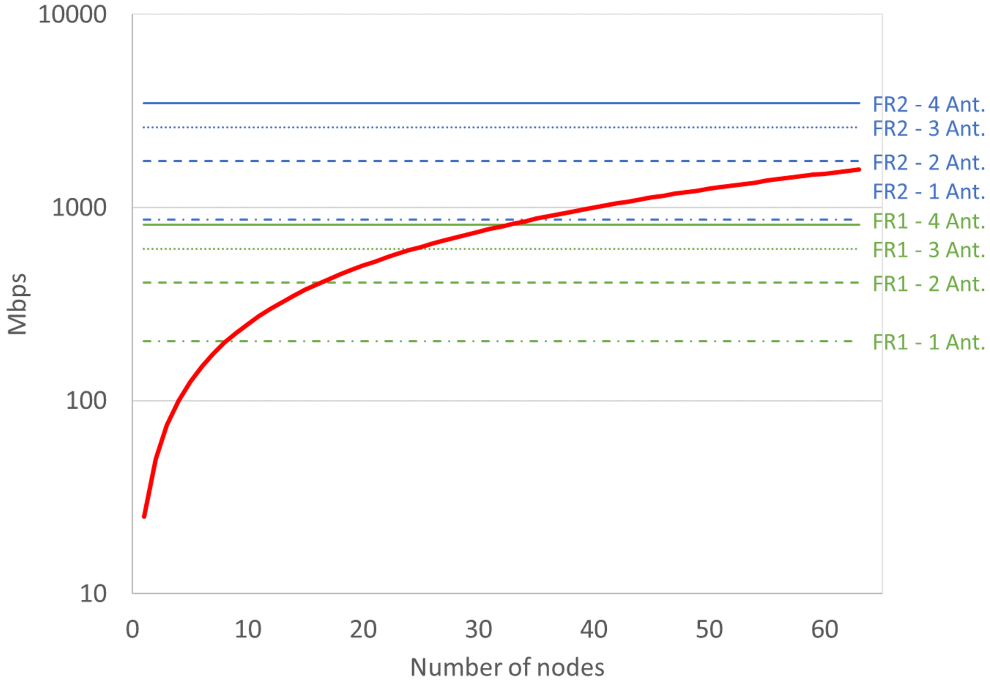


Figure 30 MCS 28 Downlink - TCMS

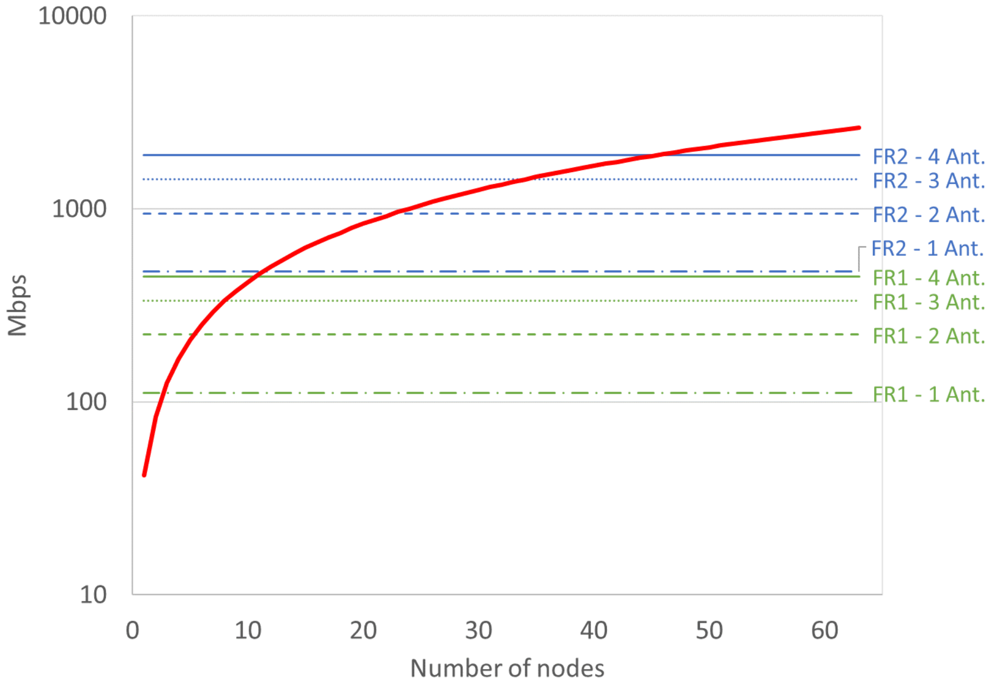


Figure 31 MCS 20 Downlink – TCMS

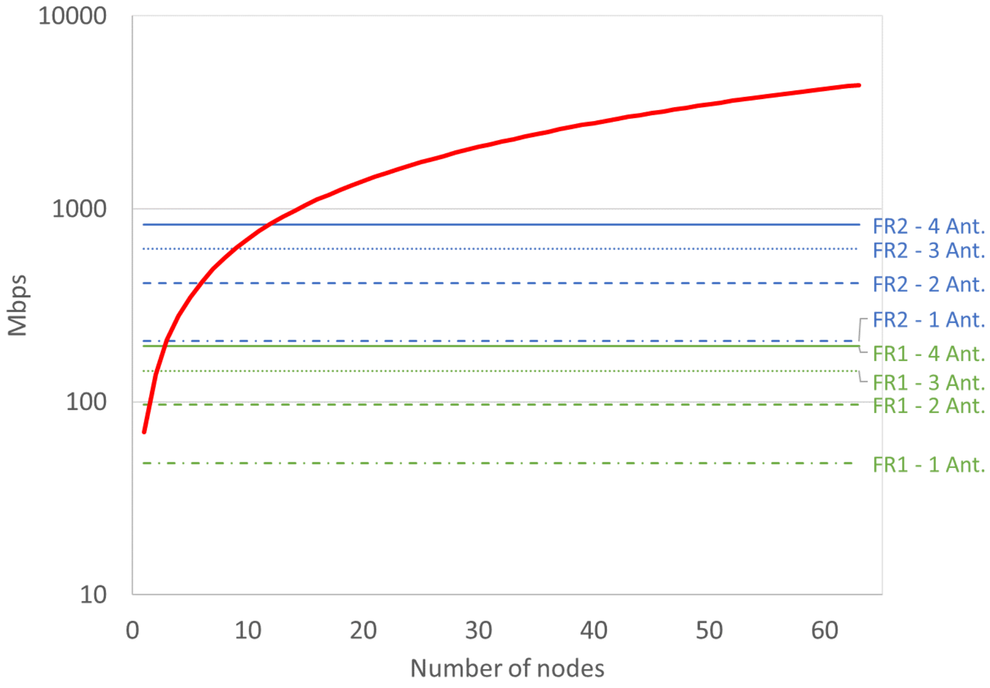


Figure 32 MCS 10 Downlink - TCMS

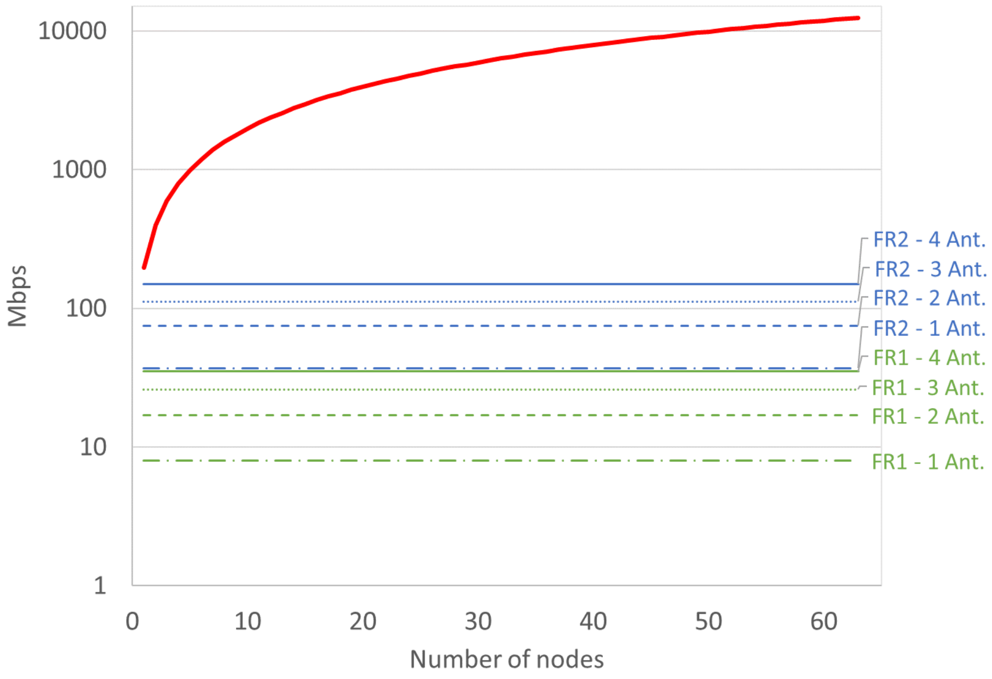


Figure 33 MCS 0 Downlink – TCMS

Matching the maximum capacity with the traffic demanded for each MCS index, the maximum number of nodes which can be managed are obtained (Figure 34 and Figure 35). As mentioned earlier, it must be noted that the maximum size of the WLTB is limited to 63 nodes, while for the WLCN it would be 30 nodes. This means that for the WLTB a minimum configuration of 2 antennas in FR2 with MCS 28 is needed in order to cover a full 63-consist train, while FR1 operation up to 22 consists is possible by using 4 antennas and MCS 28. However, it must be noted that this analysis has been made considering full bandwidth availability. This means that if the WLTB is to be operated with lower MCS values or lower number of antennas, the requirements for the WLTB should be scaled down.

Regarding WLCN, FR2 configuration with MCS 28 would cover the whole network of 30 nodes, while FR1 operation would be limited to 22 nodes, using 4 antennas and MSC 28.

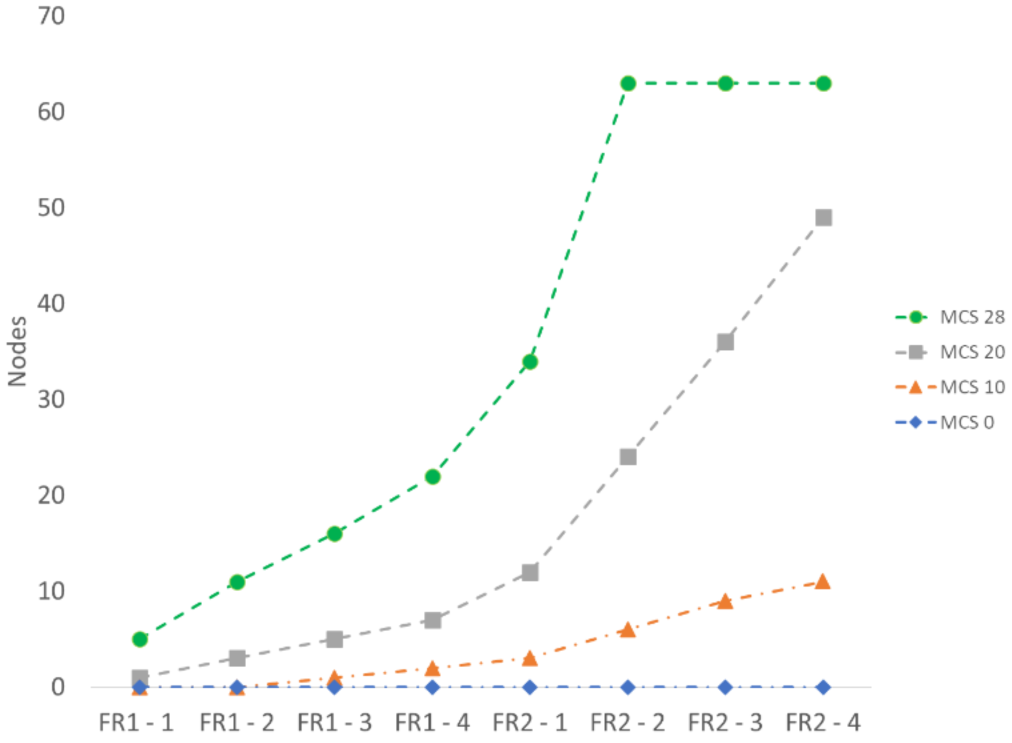


Figure 34 Maximum network size (Uplink) – TCMS

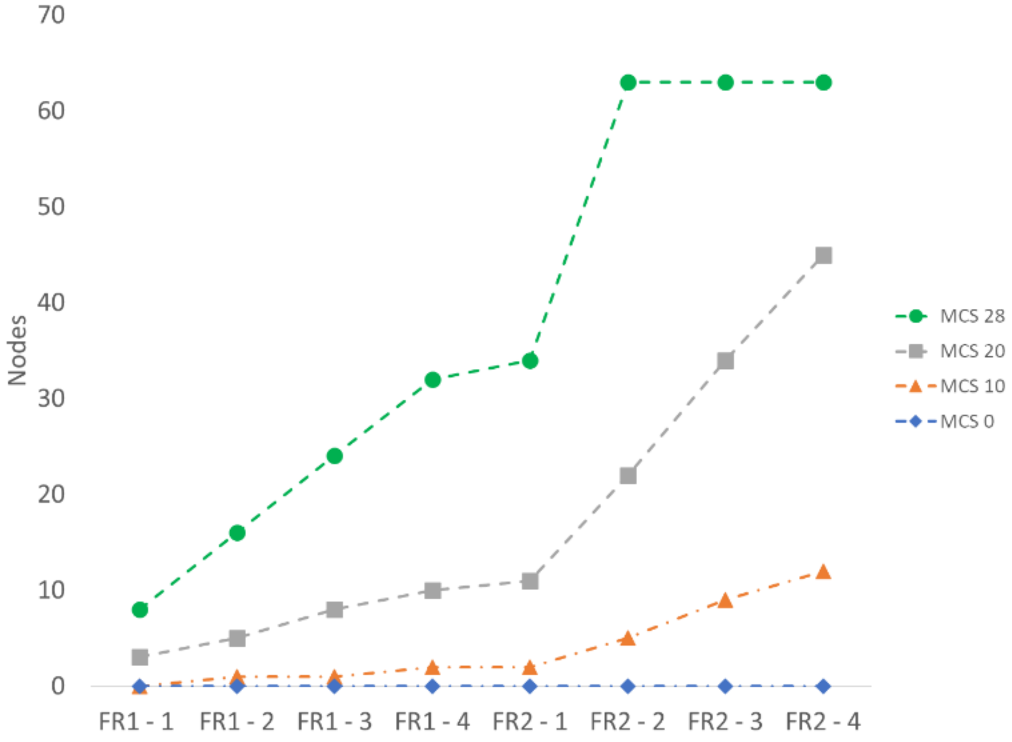


Figure 35 Maximum network size (Downlink) - TCMS

4.4.2.2 OMTS Traffic Results

Following with the same reasoning presented in 4.4.2, the maximum capacity of the 5G resource grid does not change, i.e. REs where bits are embedded are the same; however, the required traffic does change. In this case, OMTS is more demanding compared to TCMS. We can obtain the match between the maximum capacity and OMTS traffic for Uplink (Figure 36, Figure 37, Figure 38 and Figure 39) and Downlink (Figure 40, Figure 41, Figure 42 and Figure 43), as well as the maximum number of nodes that each configuration can manage for every MCS index (Figure 44 and Figure 45). These results indicate that worst-case scenario for OMTS traffic is too demanding, even for 5G technology, so more realistic scenarios should be considered in the future.

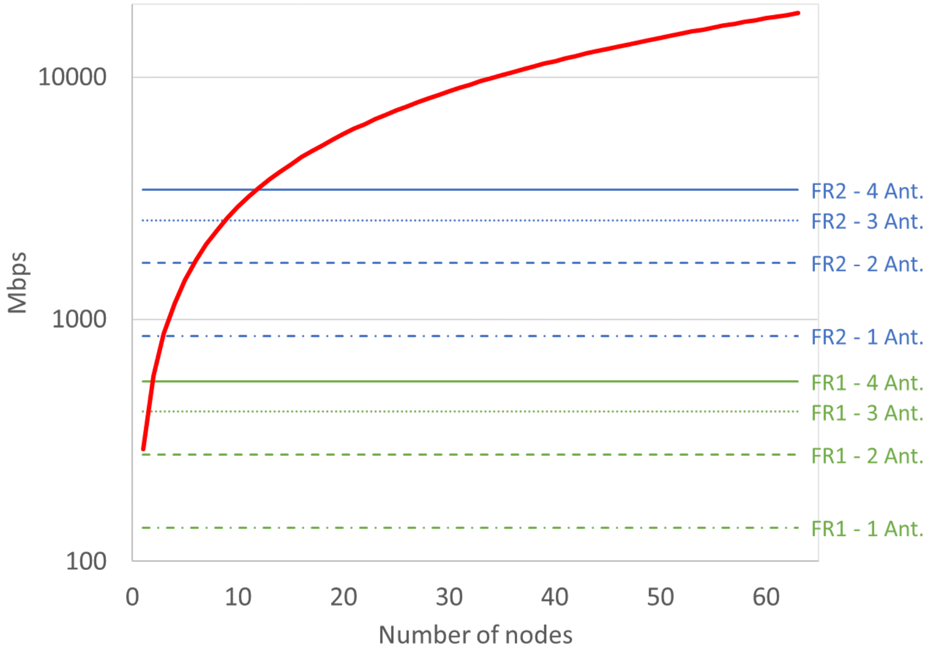


Figure 36 MCS 28 Uplink - OTMS

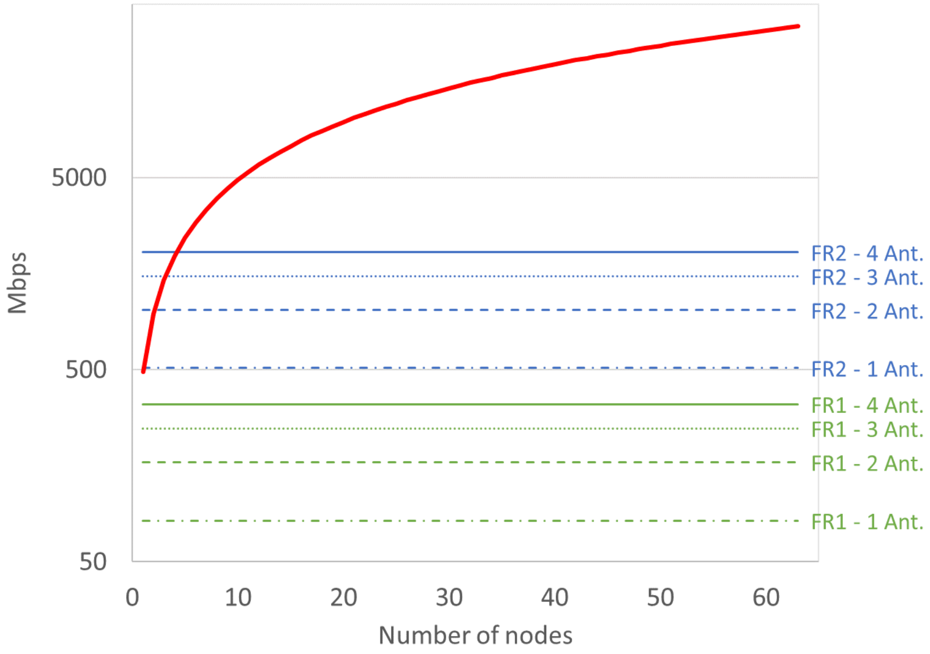


Figure 37 MCS 20 Uplink – OTMS

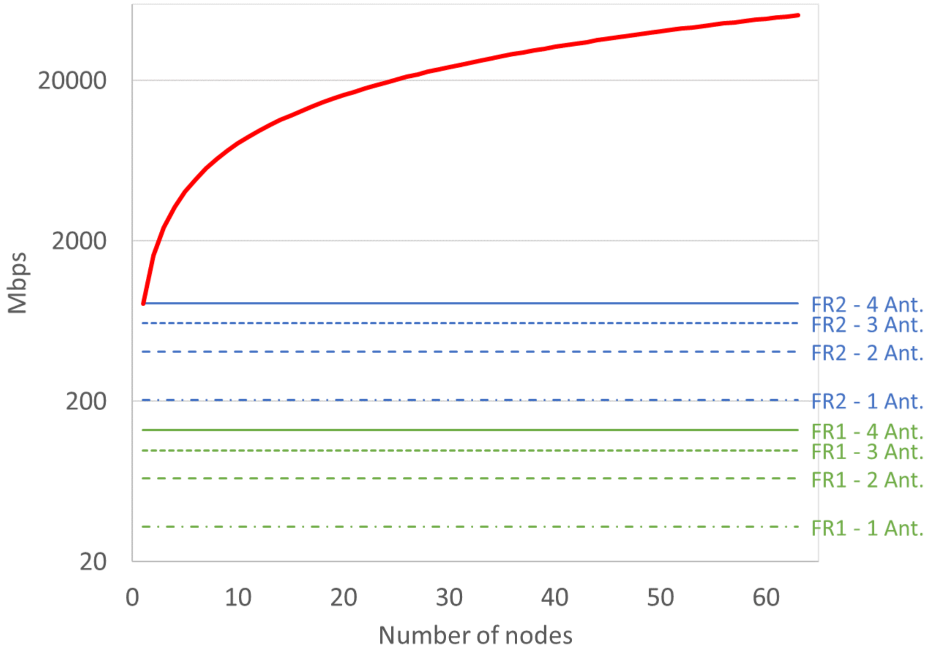


Figure 38 MCS 10 Uplink - OTMS

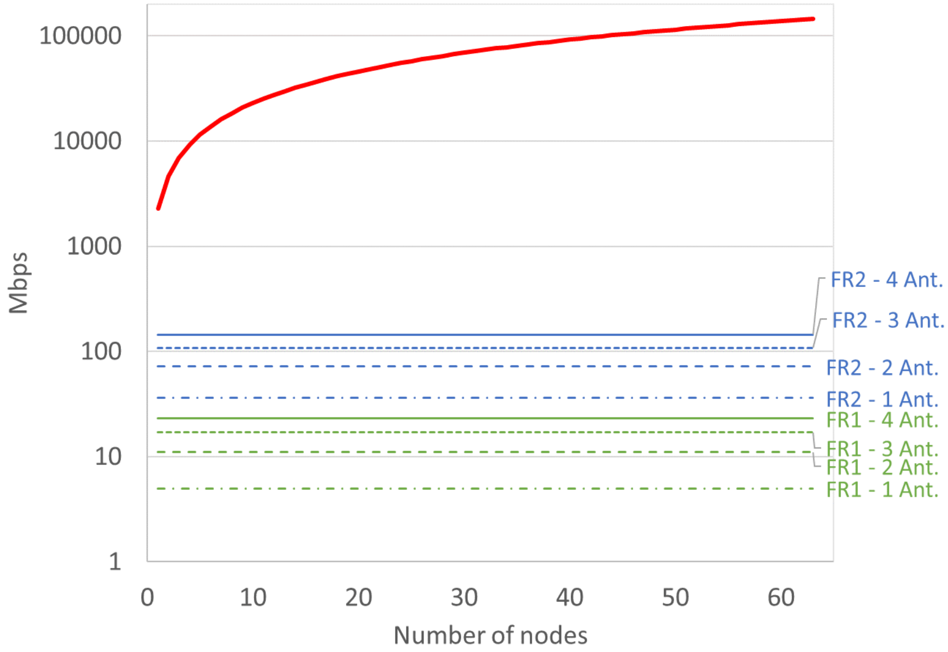


Figure 39 MCS 0 Uplink – OTMS

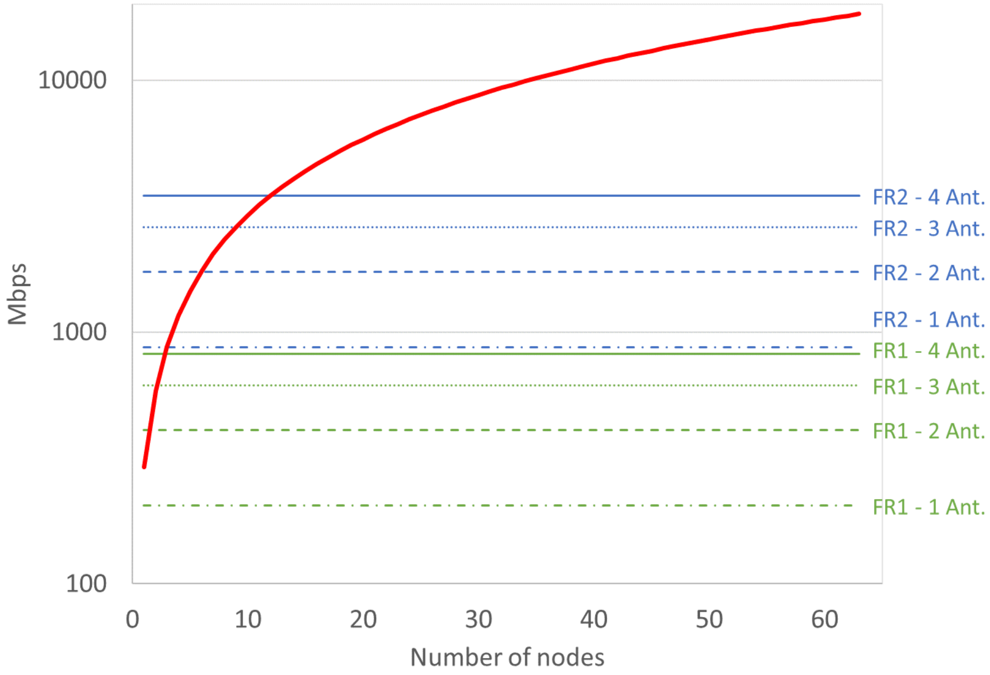


Figure 40 MCS 28 Downlink - OTMS

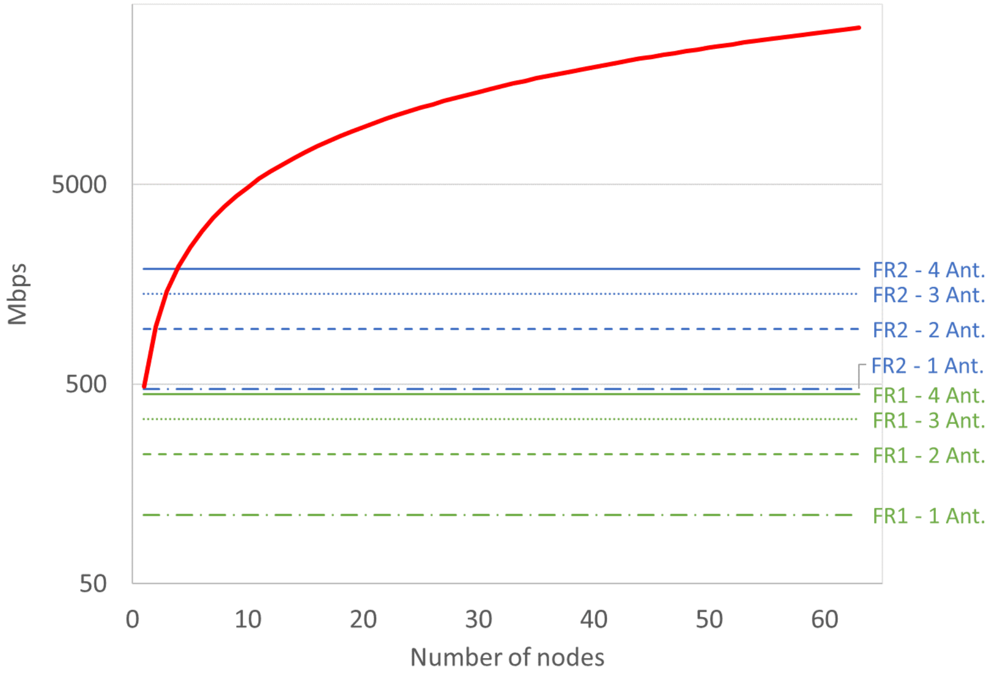


Figure 41 MCS 20 Downlink – OTMS

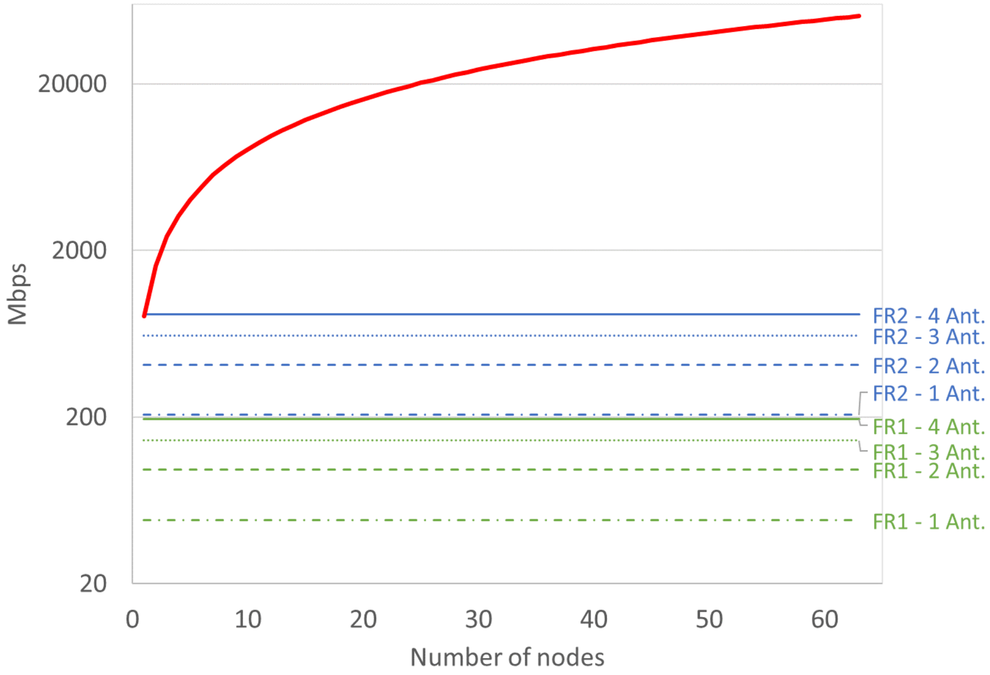


Figure 42 MCS 10 Downlink - OTMS

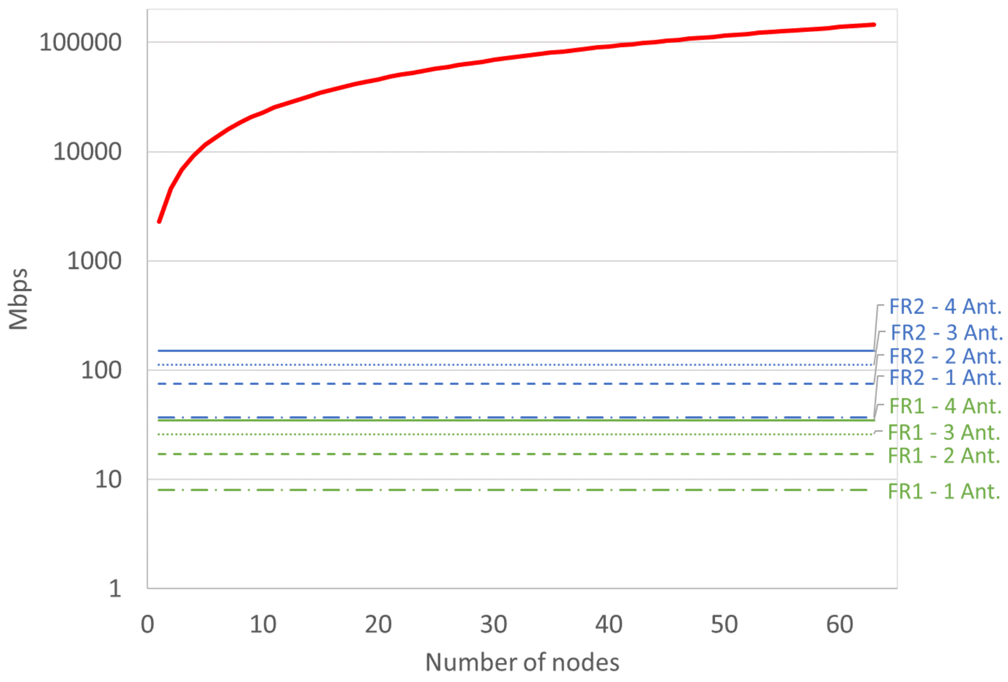


Figure 43 MCS 0 Downlink – OTMS

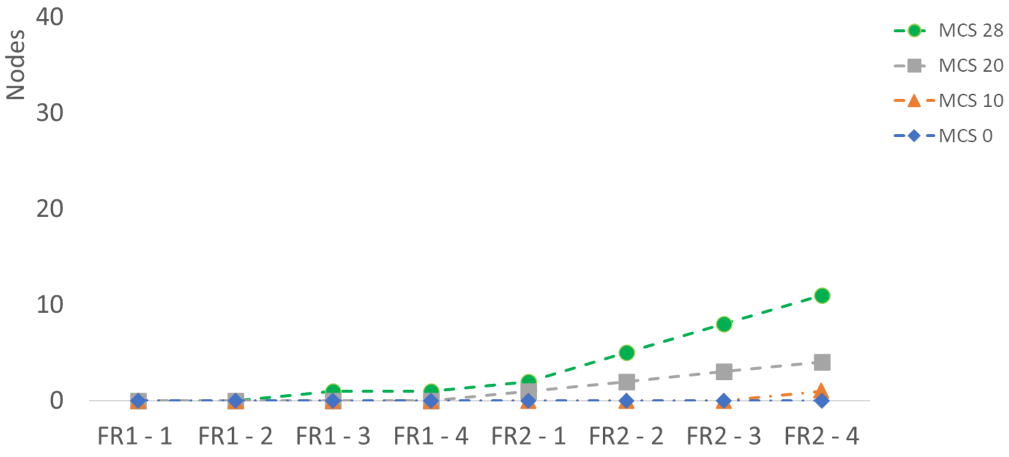


Figure 44 Maximum network size (Uplink) - OMTS

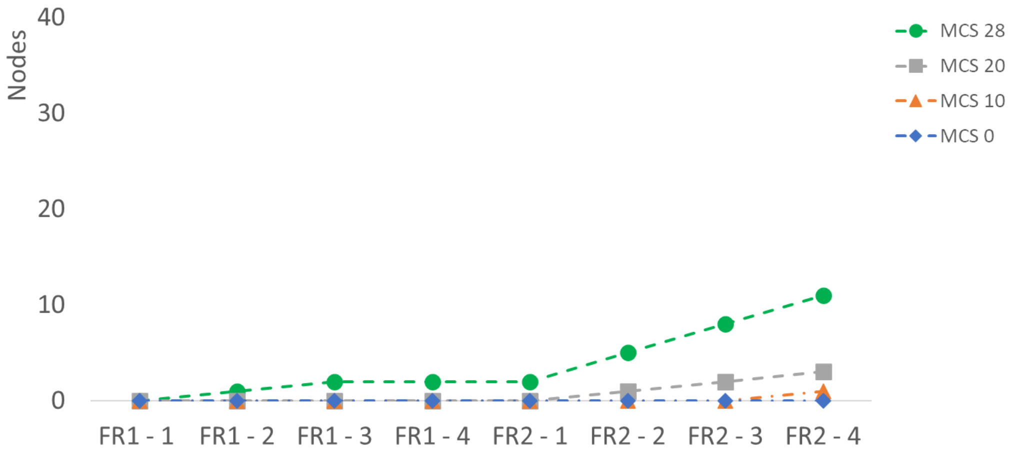


Figure 45 Maximum network size (Downlink) – OMTS

4.4.3 Latency

3GPP defines two concepts: *control plane* latency and *user plane* latency. The former defines the time a UE requires to transit from an idle state to an active one (delays combined for processes in radio and core network are considered). The latter is defined differently depending on the technical specification reviewed. In [13], it is defined as the time it takes to transfer a given piece of information form a source to a destination, measured from the communication interface from the moment it is transmitted by the source to the moment it is successfully received at the destination. In this definition, even though source/destination are not clearly defined, latency is computed as one-way and might include technologies outside 3GPP. This concept can be defined also as the one-way transit between a packet being available at the IP layer of the UE and the same packet being available at RAN, where only radio network is considered.

In [18] a evaluation of 4G and 5G technologies is done aiming at fulfilling the requirements presented by ITU in [19]. They evaluate the user plane latency defined as the time it takes to successfully deliver an application layer packet/message from the radio protocol layer 2/3 SDU ingress point to the radio protocol layer 2/3 SDU egress point. This performance is characterized in unloaded conditions and for small packet traffic (0-byte payload + IP header). Requirements are stated under two main verticals: less than 4ms for eMBB and 1ms for URLLC. These requirements are as demanding as the most critical requirement specified by CONNECTA-2. This evaluation is carried out as shown in Figure 46. In Downlink, the processing delay of the base station, a frame alignment time, TTI for DL transmission and UE processing delay are computed. Also, HARQ time is computed in case a retransmission is required. Results are presented assuming an error probability.

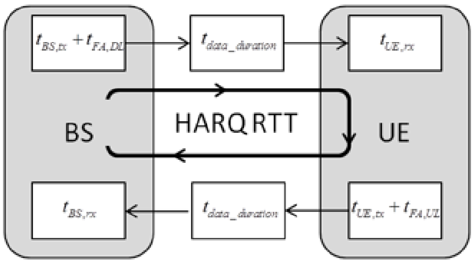


Figure 46 User plane procedure for evaluation in [18]

Results show that for this configuration 5G can cope with the traffic of this analysis under several configurations (FDD, different frame structures of TDD, considering supplementary uplink).

An analogous evaluation for Uplink is performed. In this case, in order to fulfil the requirements grant-free scheduling is done for same configurations as in the Downlink evaluation. For Uplink, it is noticeable that the standard introduces several timers that govern the behaviour of latency (K0, K1, K2). These introduce the time spent between DL allocation and data, delay between reception of data and HARQ-ACK feedback on Uplink, and delay between grant reception and corresponding UL first data transmission. These timers are derived from UE capabilities, such as N1 or N2, which depend on the configuration of the numerology and the capabilities of the UE itself. These processing delays specify the number of symbols required for the UE processing from the end of DL data to the earliest possible start of the corresponding ACK/NACK transmission (N1), and (N2) the number of symbols required from the receiving of the grant to the earliest possible start of the corresponding UL data. Therefore, scheduling timer values should never fall behind the N1 or N2 values. Examples of these values can be found in [20], [21], where for diverse configurations N1 and N2 values are proposed (e.g. slot based, non-slot based, carrier aggregation, etc.). Also in [20], other issues related to overall E2E latency are addressed, such as the maximum number of HARQ processes admitted by a UE per cell.

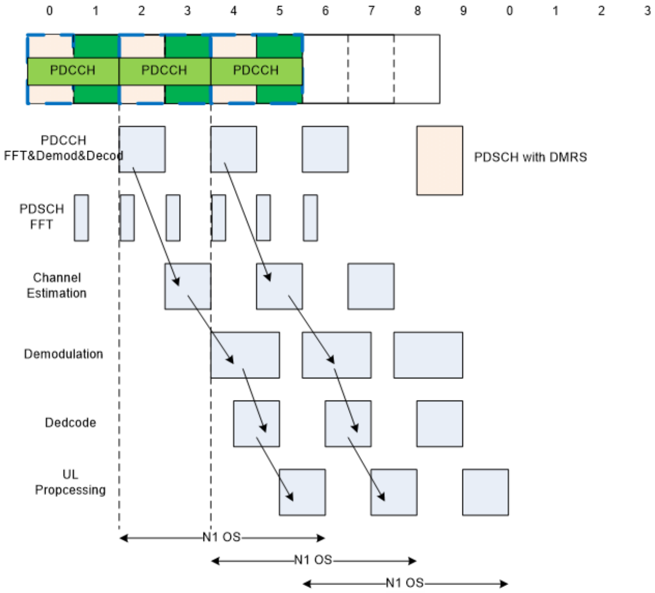


Figure 47 Non-slot based scheduling (2OS) processing time analysis. [21]

All in all, although latency is one of the most restrictive requirements, provided results show that 5G can meet these requirements under specific circumstances such as those indicated in the works above (e.g. unloaded conditions, small packet traffic, or grant-free scheduling).

4.5 5G V2X

NR-V2X is presented by 3GPP in Rel.16 as an extension of LTE-V2X technology. It has several enhancements, such as a more robust NR physical layer, unicast and groupcast communication, dynamic resource allocation and a new Physical Sidelink Feedback Channel (PSFCH) for HARQ [27]. Additionally, Rel. 17 has a proposal for a multi-hop NR V2X relaying. One use case is the wagon use case, and it can be applied either for creating a mesh for WLTB or a tree-based structure for WLCN.

For the purpose of analysing the applicability of 5G-V2X for WLTB and WLCN, and following with the methodology adopted in previous sections, 3GPP standards have been analyzed first, and after that a resource-grid analysis is presented. Finally, a latency and resource-management review is done.

4.5.1 Use Case Analysis

In TS-122 186 [24] service requirements are specified to enhance 3GPP support for V2X in several areas. Analysing all scenarios, Vehicles Platooning is selected as a reference for being the best approximation to the railway scenarios. From the analysis carried out, which can be seen in Table 9, it is observed that all types of traffic cannot be covered with 5G-V2X (i.e. the enhancements from 4G-V2X are not enough to accomplish CONNECTA-2 requirements).

4.5.2 Resource Grid Analysis

Because of being an enhancement of 4G SideLink, 5G-V2X (Release 16) presents some novelties. In that sense, it can be deployed in two frequency ranges: FR1 (below 7 GHz) and FR2 (above 24 GHz). Besides, 5G-V2X makes use of the new physical layer introduced in 5G infrastructure-based mode, allowing new slot configurations which increase enormously the capacity thanks to the numerology concept.

Taking this into consideration, it could be claimed that vehicular-mode and 5G infrastructure-mode capacities are the same, and at a first glance, the gross calculation of REs is identical for both systems (91728 REs for FR1 and 354816 REs in FR2). However, the actual capacity changes due to the fact that physical channels and reference signals in NR SideLink have differences with respect to 5G infrastructure-based. Apart from that, it must be considered that V2X resource allocation is done in subchannels formed by sets of RBs, contrary to 5G infrastructure-based mode where resource allocation in done in REs.

In order to determine the number of REs allocated for PSSCH (Physical SideLink Shared Channel), where traffic bits are embedded, the procedure specified in [26, Clause 8.1.3.2] is applied. From there, it can be claimed that a UE determines the total of REs allocated within a slot for PSSCH by:

$$N_{RE} = N'_{RE} * n_{pRB} - N_{RE}^{SCI,1} - N_{RE}^{SCI,2}$$

Eq. 1 Total number of REs allocated for PSSCH

$$N'_{RE} = N_{SC}^{RB} * (N_{symb}^{sh} - N_{symb}^{PSFCH}) - N_{oh}^{PRB} - N_{RE}^{DMRS}$$

Eq. 2 Number of REs allocated for PSSCH within a PRB

Where:

- n_{pRB} is the number of allocated PRBs for the PSSCH. For FR1 and a SCS of 30 kHz, it implies 273 RBs meanwhile for FR2 and a SCS of 120 kHz it supposes 264RBs.

- $N_{RE}^{SCI,1}$ is the total number of REs occupied by PSCCH and PSCCH DMRS.
  (SCI occupies 2 RBs per subchannel).

- $N_{RE}^{SCI,2}$ is the number of coded modulations symbols generated for 2nd – stage SCI transmissions.
  (SCI occupies 2 RBs per subchannel).

- N_{SC}^{RB} = 12 (number of subcarriers in a physical resource block).

- N_{symb}^{sh} = 12 (*sl-LengthSymbols-2),* where *sl-LengthSymbols* is the number of SideLink symbols within the slot provided by higher layers.

- N_{symb}^{PSFCH} is determined by higher layers. Depending on the higher layer parameter labelled as *sl-PSFCH-Period* it can be {0,3}.

- N_{oh}^{PRB} is determined by higher layers. Depending on the higher layer parameter labelled as *sl-X-Overhead* it can be {0,3,4,9}.

- N_{RE}^{DMRS} is determined by higher layers. Depending on the higher layer parameter labelled as *sl-PSSCH-DMRS-TimePattern* it can be {12, 18, 24, 15, 18, 21, 18}.

As it is claimed in 4.2.2, due to the 5G resource grid variability (i.e: numerology), the following assumptions are done:

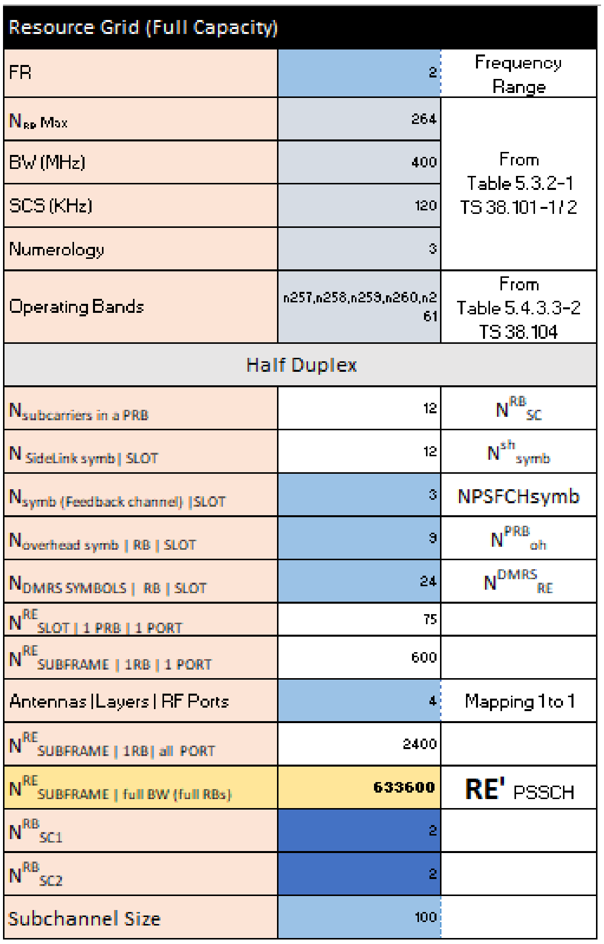
1. It is assumed that the whole bandwidth (i.e. 400 MHz) is available for SideLink.
2. The most restrictive configuration is adopted regarding the amount of resources occupied by control channels and signals.
3. It is considered that the streams from codewords codifications are directly mapped into RF ports and physical antennas, allowing spatial multiplexing.
4. Among all possible configurations, a subchannel size of 100 RBs is considered.

An Excel spreadsheet is programmed with this configuration (see snapshot in Figure 48). From there, the capacity offered (Rb, in Mbps) by resultant REs is obtained, where PSSCH would be codified after subtracting REs occupied by reference signals and control channels.

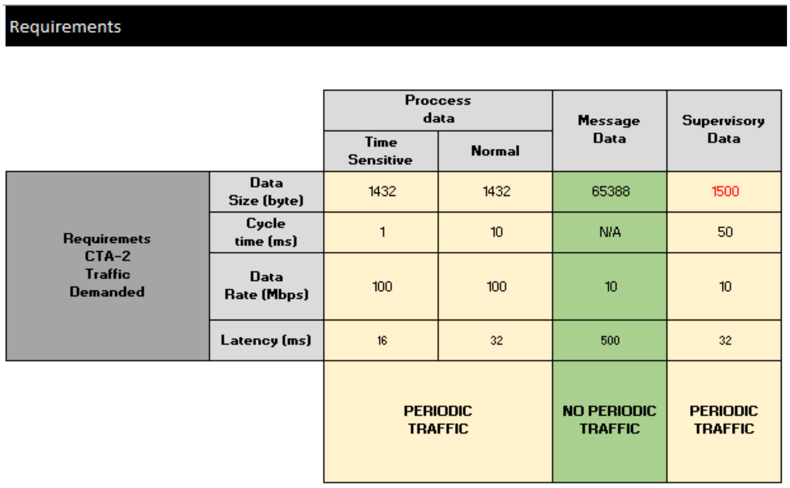
Capacity is dependent on the MCS index and spatial configuration (FRxx, yAnnt), either for TCMS (see Figure 49, Figure 50, Figure 51, Figure 52) or OMTS (see Figure 54, Figure 55, Figure 56, Figure 57). MCS indexes 28, 20, 10 and 0 have been selected as representatives.

Matching the maximum capacity for each configuration with the traffic demanded for each MCS index are obtained the maximum number of nodes that each configuration which can be managed for each MCS index (see Figure 53, Figure 58).

When considering these results, it should be noted that the weakest point in V2X, either LTE-V2X or NR-V2X, is the scheduler. In fact, it has huge impact on the analysis of the resource management. V2X scheduler inherits from LBT (Listen Before Talk) algorithms which do not guarantee resources available when a UE wants to transmit. Because of that, the outcomes presented in the following points must be considered in an idealistic setup; it means that in a real setup these capabilities in terms of bit rate could be significantly reduced.

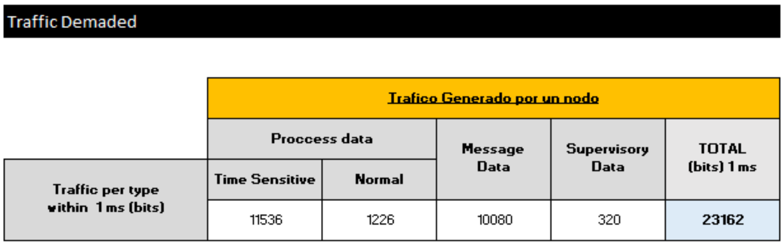


Resource Grid (Full Capacity)		
FR	2	Frequency Range
N_{RB} Max	264	From Table 5.3.2-1 TS 38.101-1/2
BW (MHz)	400	
SCS (KHz)	120	
Numerology	3	
Operating Bands	n257,n258,n259,n260,n261	From Table 5.4.3.3-2 TS 38.104
Half Duplex		
$N_{subcarriers\ in\ a\ PRB}$	12	N^{RB}_{SC}
$N_{SideLink\ symb\ \mid\ SLOT}$	12	N^{sh}_{symb}
$N_{symb\ (Feedback\ channel)\ \mid SLOT}$	3	NPSFCHsymb
$N_{overhead\ symb\ \mid\ RB\ \mid\ SLOT}$	9	N^{PRB}_{oh}
$N_{DMRS\ SYMBOLS\ \mid\ RB\ \mid\ SLOT}$	24	N^{DMRS}_{RE}
$N^{RE}_{SLOT\ \mid\ 1\ PRB\ \mid\ 1\ PORT}$	75	
$N^{RE}_{SUBFRAME\ \mid\ 1RB\ \mid\ 1\ PORT}$	600	
Antennas |Layers | RF Ports	4	Mapping 1 to 1
$N^{RE}_{SUBFRAME\ \mid\ 1RB \mid\ all\ PORT}$	2400	
$N^{RE}_{SUBFRAME\ \mid\ full\ BW\ (full\ RBs)}$	**633600**	**RE'** PSSCH
N^{RB}_{SC1}	2	
N^{RB}_{SC2}	2	
Subchannel Size	100	



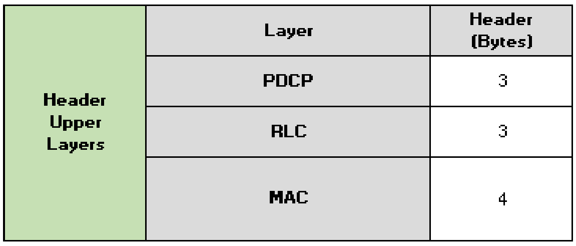
Requirements

		Proccess data		Message Data	Supervisory Data
		Time Sensitive	Normal		
Requiremets CTA-2 Traffic Demanded	Data Size (byte)	1432	1432	65388	1500
	Cycle time (ms)	1	10	N/A	50
	Data Rate (Mbps)	100	100	10	10
	Latency (ms)	16	32	500	32
		PERIODIC TRAFFIC		NO PERIODIC TRAFFIC	PERIODIC TRAFFIC



Traffic Demaded

	Trafico Generado por un nodo				
	Proccess data		Message Data	Supervisory Data	TOTAL (bits) 1 ms
	Time Sensitive	Normal			
Traffic per type within 1 ms (bits)	11536	1226	10080	320	**23162**



	Layer	Header (Bytes)
Header Upper Layers	PDCP	3
	RLC	3
	MAC	4

Figure 48 Dynamic Excel sheet snapshot (V2X)

4.5.2.1 TCMS Traffic Results

Table 12 summarizes the maximum capacity offered by each configuration (Frequency Range / Number of TX antennas) in terms of the MCS Index.

			MCS Index			
		Antennas	**0**	**10**	**20**	**28**
SideLink	**FR1**	**1**	10	54	136	227
		2	19	109	272	455
		3	29	163	408	682
		4	38	218	544	910
	FR2	**1**	37	210	526	880
		2	74	421	1052	1760
		3	111	631	1579	2640
		4	149	842	2105	3519

Table 12. V2X Maximum capacity (Mbps) – TCMS

Following the same reasoning as in 4.4.2, the maximum capacities of 5G-V2X and the required TCMS traffic values for different number of nodes are obtained and plotted in Figure 49, Figure 50, Figure 51 and Figure 52. From them, the maximum number of nodes (max network size) supported for each configuration is presented in Figure 53.

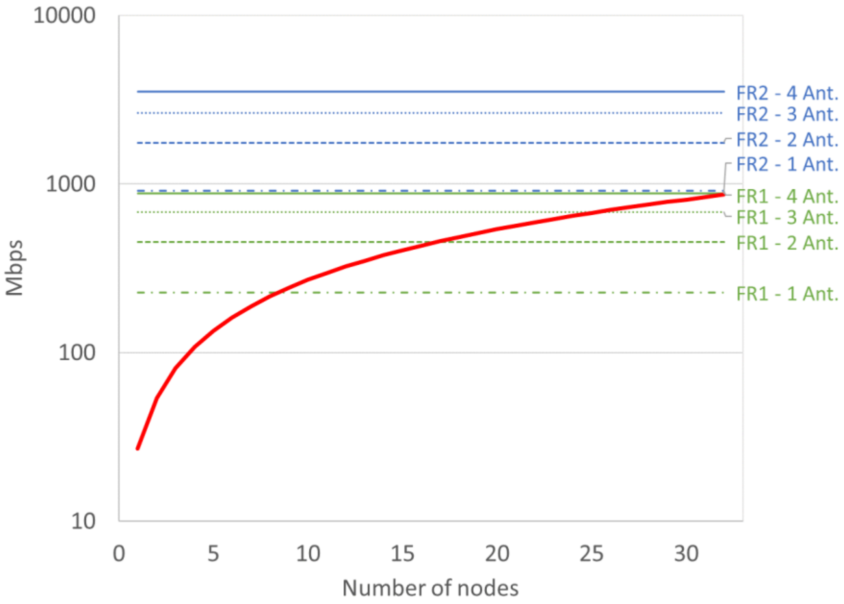


Figure 49 MCS 28 SideLink - TCMS

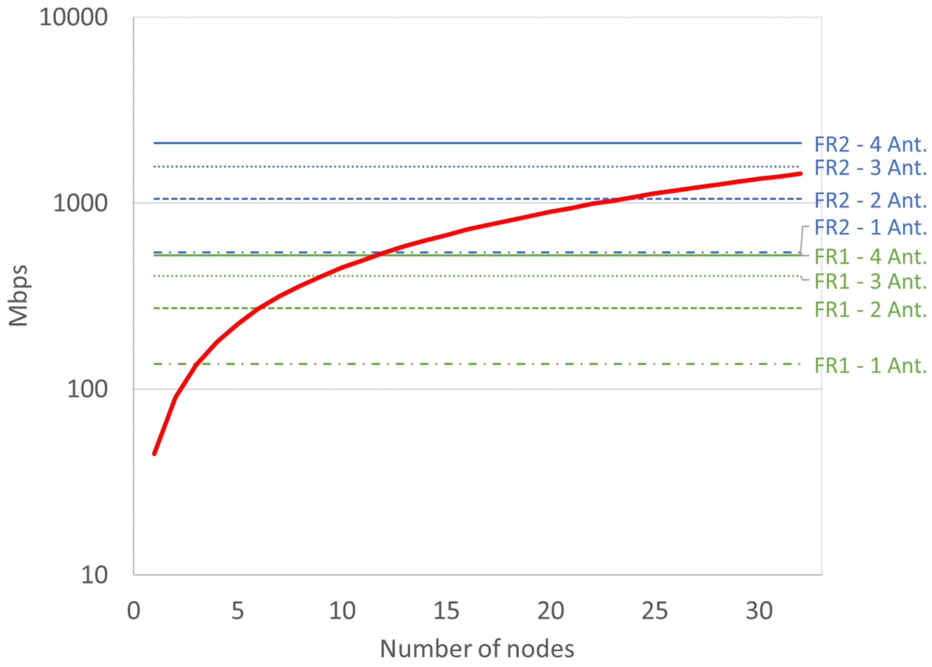


Figure 50 MCS 20 SideLink – TCMS

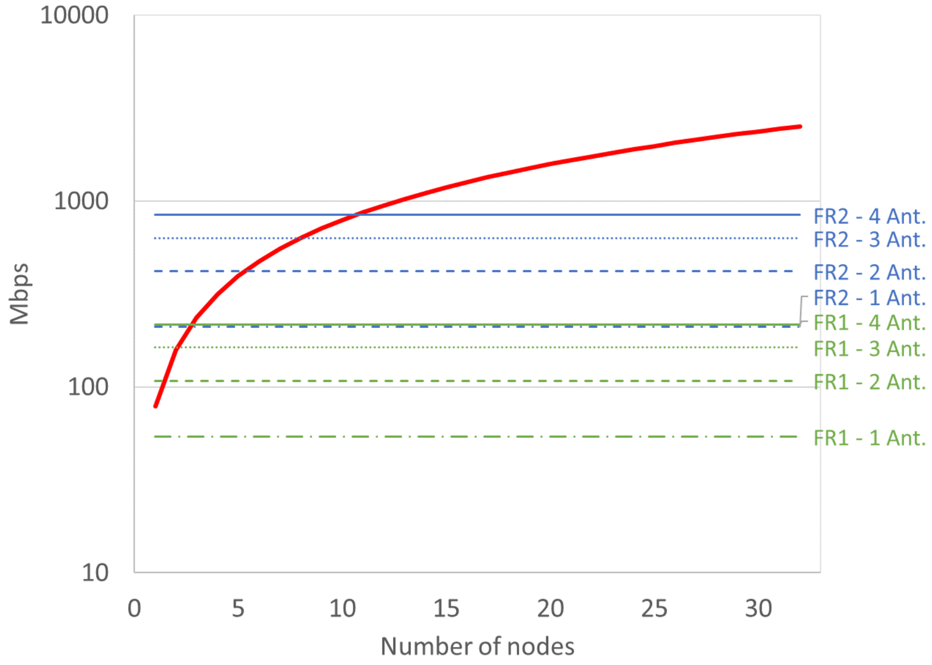


Figure 51 MCS 10 SideLink - TCMS

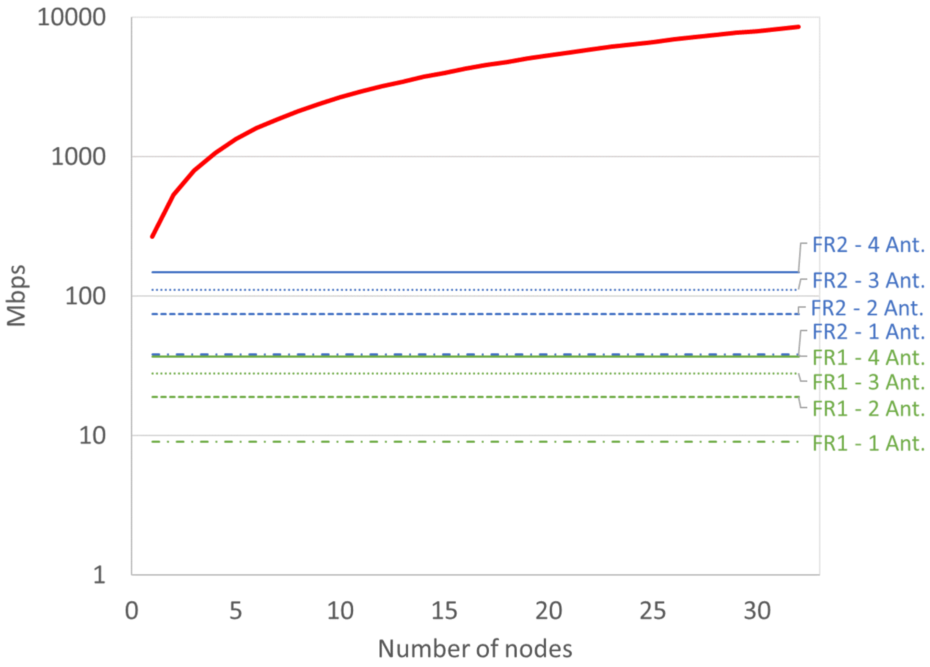


Figure 52 MCS 0 SideLink – TCMS

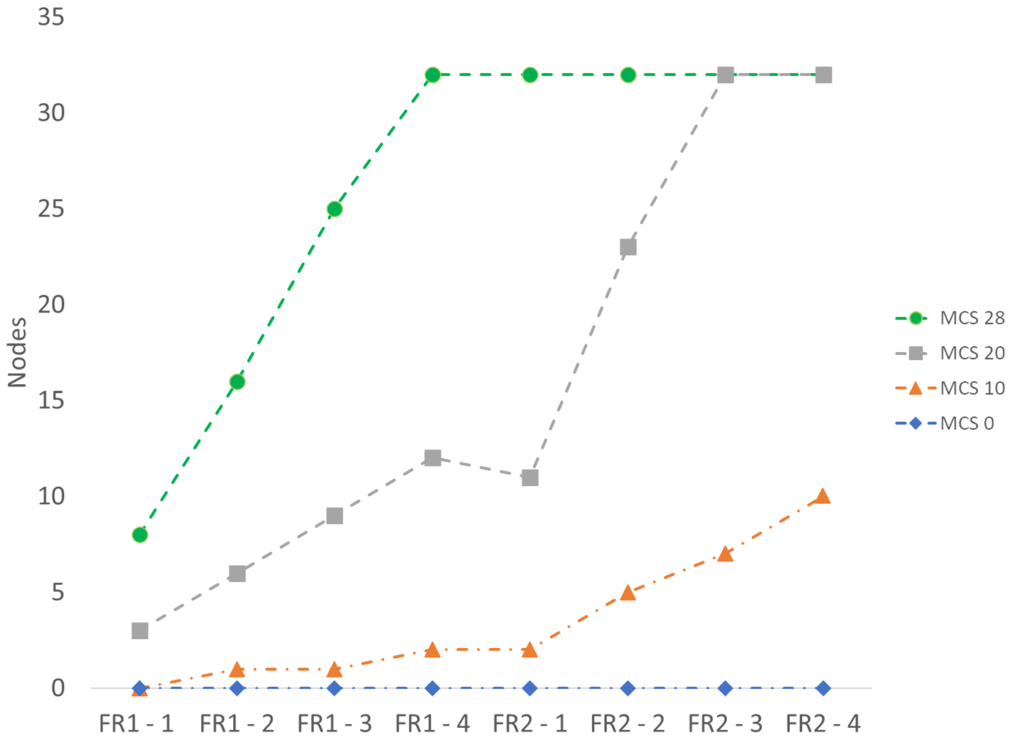


Figure 53 Maximum network size (SideLink) – TCMS

4.5.2.2 OMTS Traffic Results

In the same way, the capacity evolution for each configuration of MCS (Figure 54, Figure 55, Figure 56, Figure 57) and network size analysis (Figure 58) is done for OTMS traffic.

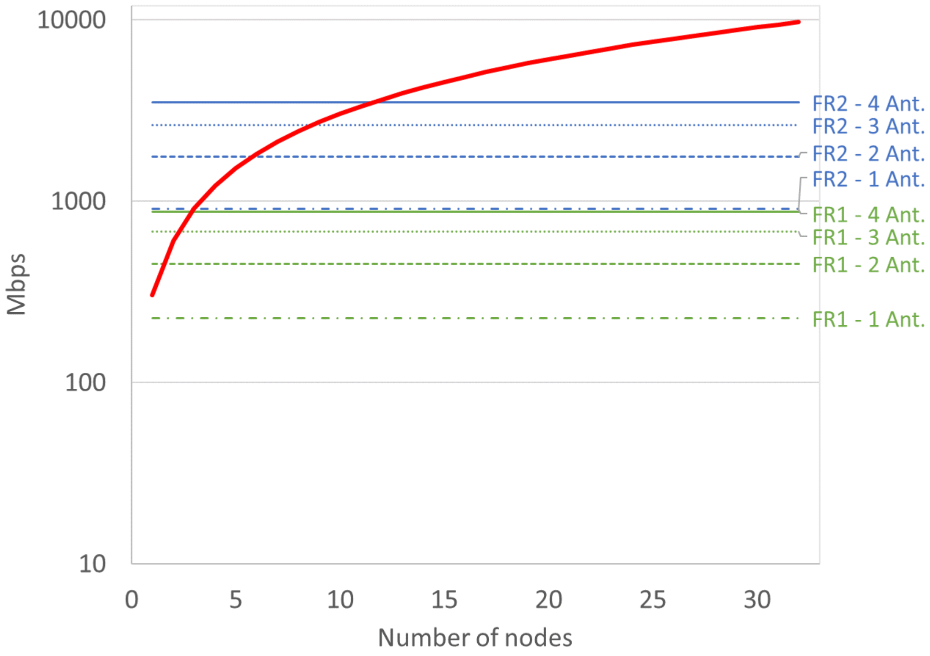


Figure 54 MCS 28 SideLink – OMTS

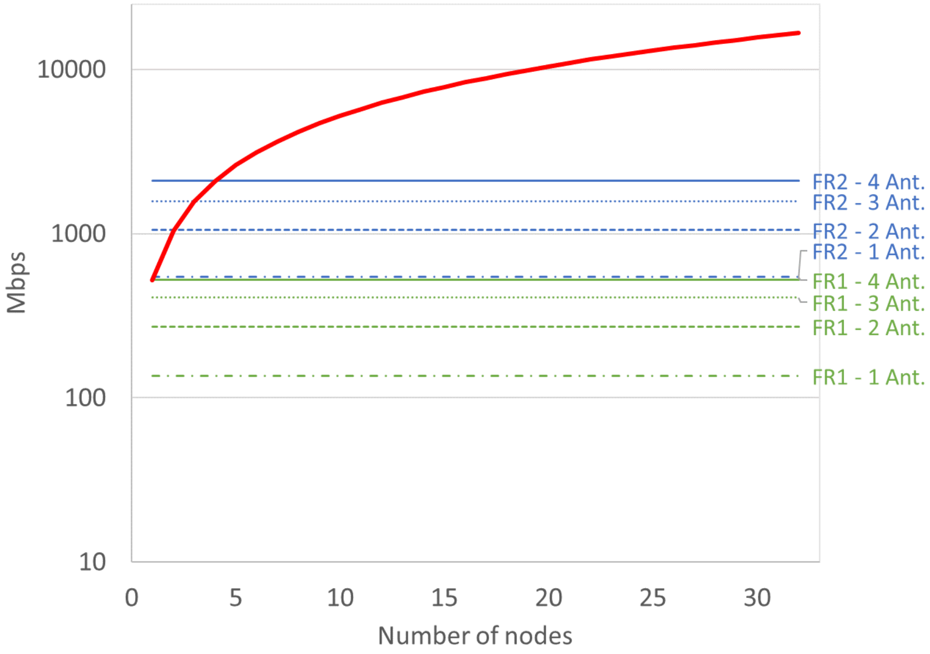


Figure 55 MCS 20 SideLink - OMTS

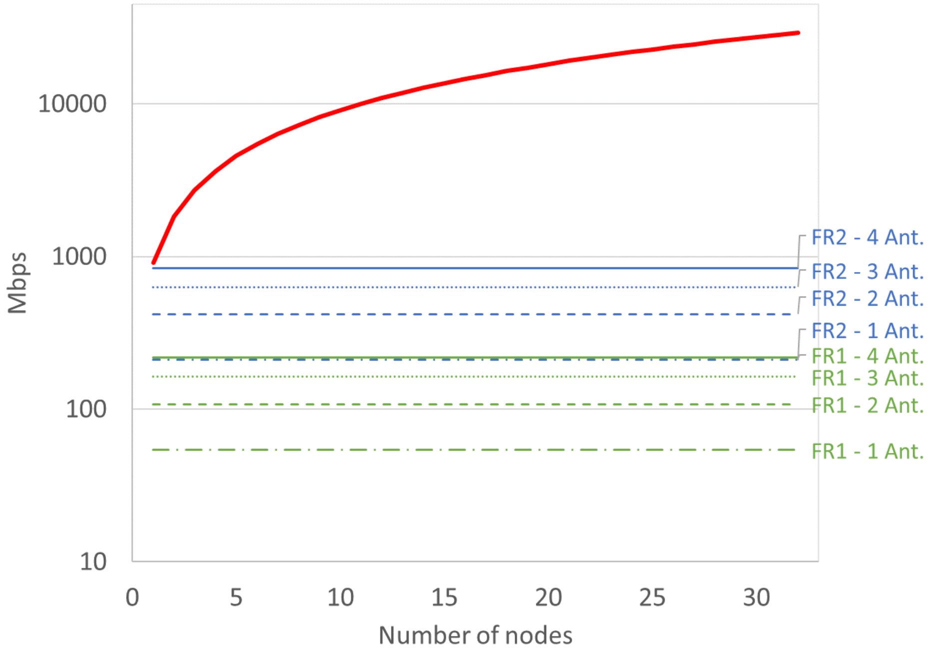


Figure 56 MCS 10 SideLink – OMTS

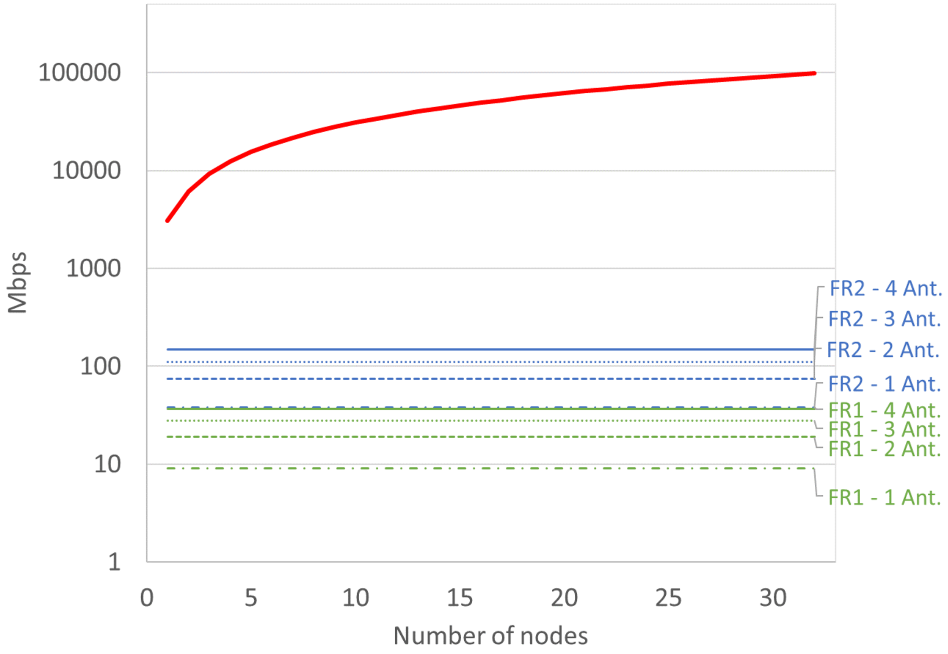


Figure 57 MCS 0 SideLink - OMTS

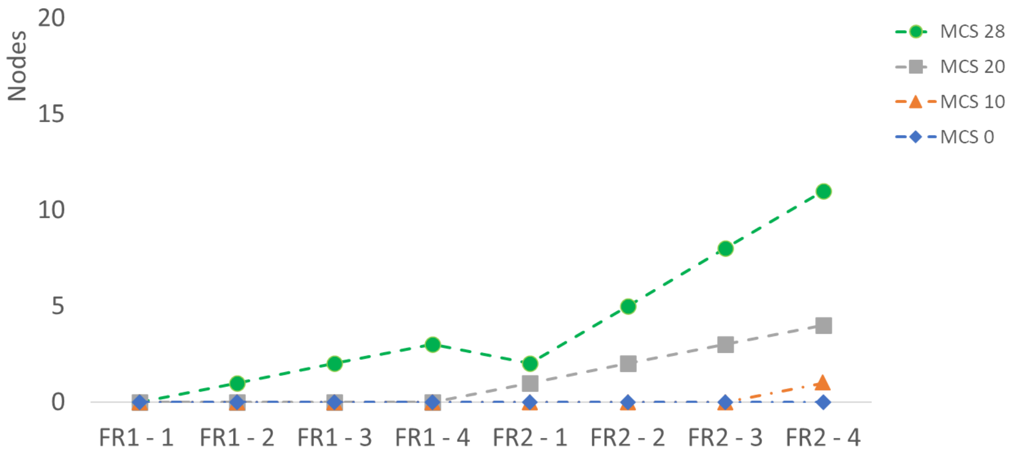


Figure 58 Maximum network size (SideLink) – OMTS

4.5.3 Latency and resource management

In terms of resource allocation, NR SideLink (5G-V2X) has two main working modes (mode 1 and 2) and four sub-modes (2a, 2b, 2c and 2d). In mode 1, the gNB manages resource allocation, while in mode 2 the UEs autonomously manage these resources, supporting direct vehicular communication (i.e. without gNodeB).

Mode 2a is the most similar one to mode 4 in 4G-V2X. In this mode each UE selects its own resources. Regarding latency, the biggest constraint is the scheduler algorithm (based on listening before talk procedures, see 4.3.3), because of the sensing and selection window implemented (see Figure 25). From this perspective, there are no modifications in the latest 3GPP releases in terms of resource allocation; nevertheless, there are some discussions still opened in 3GPP about it [25] with the goal of studying technical solutions for SideLink resource allocation. In [25], the major principles of resource allocation are debated, and some proposals are done as well. NR-V2X resource allocation mode-2 is pointed out for traffic division in periodic and aperiodic flows. The presented algorithm includes some modifications from 4G SideLink according to the type of traffic, varying the windows sizes depending on it (periodic or aperiodic traffic). On the one hand, Large Scale (Long Term) for periodic traffic where resource selection is based on long-term historic observation. On the other hand, Small Scale (Short Term) for aperiodic traffic selecting resources based on recent/instantaneous sensing results (Figure 59).

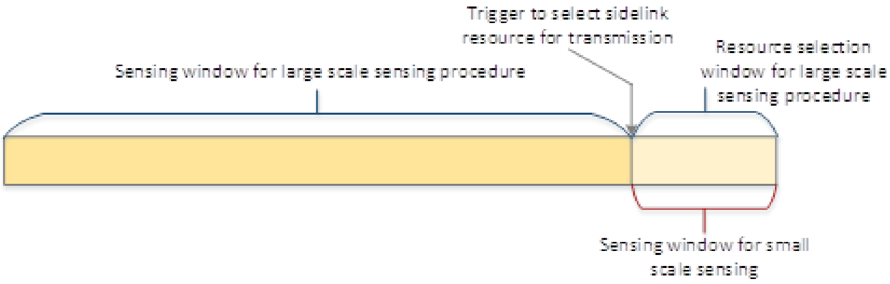


Figure 59 Large/Small sensing window

In Mode 2d, a UE performs resource allocation for a group of UEs in its vicinity, being especially useful in platooning application where vehicles move along same direction with small relative velocities [28].

Two research lines based on Mode 2a and Mode 2d are presented here which could be beneficial for the current analysis.

4.5.3.1 Improved NR-V2X mode 2a with STDMA

Mode 2a from NR-V2X, which inherits from LBT (Listen Before Talk) algorithms, has issues in terms of reliability and resilience under heavy communication loads and half-duplex limitations.

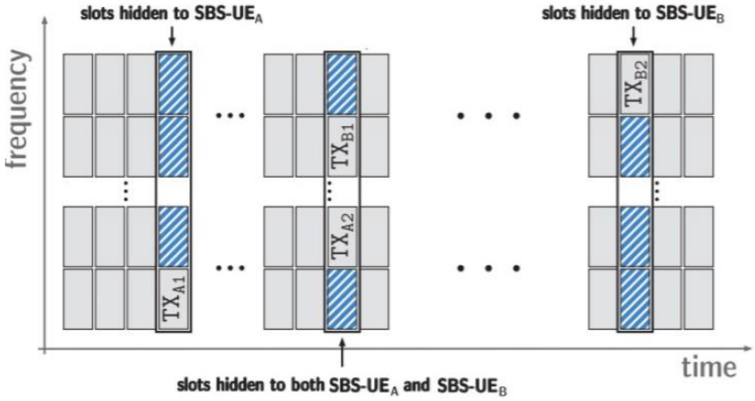


Figure 60 Half-Duplex impairments for LTE/NR V2X [27]

To overcome these limitations, several studies show STDMA (Self-organized Time-Division Multiple Access) as a potential alternative scheduler for LTE-V2X. In Figure 61 it can be observed how the STDMA resilience is incremented (higher PDR: Packet Delivery Ratio) in comparison to SP-LBT when the load (i.e vehicle density expressed in vehicles per km) is increased. From here, it can be observed that 99% of PDR is limited because of the impact of half-duplex impairments on both schedulers, which cannot be cancelled without full duplex radio front-ends. However, it is possible to improve the schedulers by choosing which UE conflicts. In that sense, SH-STDMA places resources conflicting as far away as possible, reducing this effect (see Figure 61 where 99,9% of PDR is reached, meeting one of the URLL V2X communication criteria).

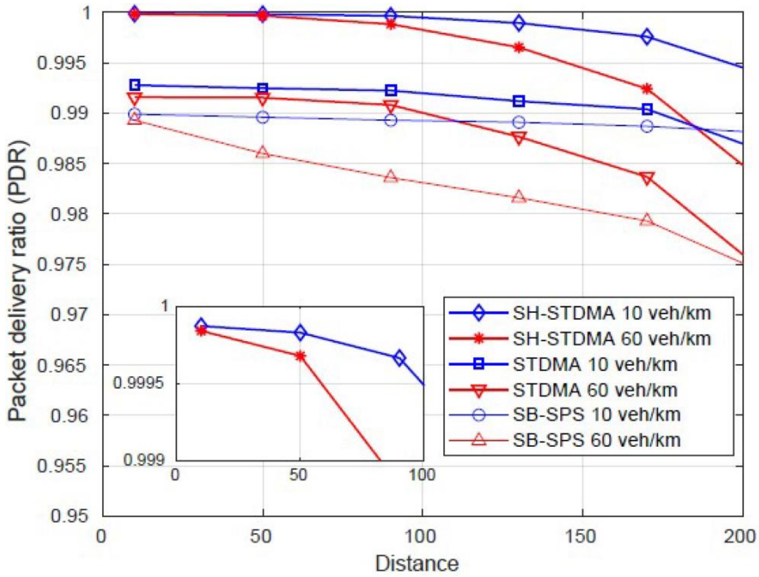


Figure 61 SP-LBT, STDMA and SH-STDMA comparison

It must be noted that NR V2X rel.16 has only mode 2a and any other modes are left to future releases (most likely rel.18).

4.5.3.2 Cluster-based scheduling NR-V2X mode 2d

In mode 2d, the resource selection by one UE for a group of them (see 4.5.3) must be done carefully to avoid collisions or interferences. Because of that, several approaches are being carried out reusing resources depending on the geographical zone clustered. Thanks to this perspective, resource allocation is different in each geographical zone, what implies higher capacities and reduction of interferences and collisions (see Figure 62).

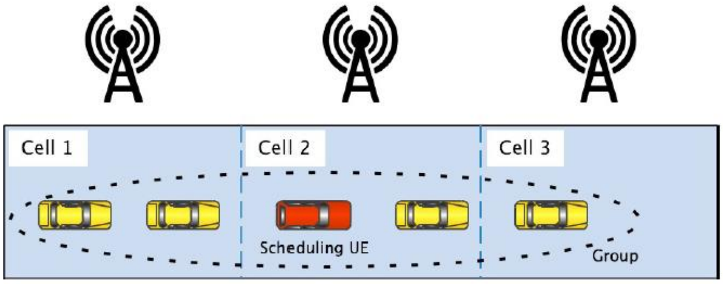


Figure 62 5G-V2X mode 2d (cluster-based scheduling) [28]

Chapter 5 Virtual Coupling

Several activities related to Virtually Coupled Train Sets (VCTS) are currently being done in X2RAIL-3 and MOVINGRAIL projects. VCTS relies basically on Train-to-Train (T2T) wireless links; therefore, considering the analysis done in Chapter 2 for the integration of WLTB and T2G links, it seems reasonable from an architecture point of view to propose the integration of these three communication systems in the ACS node (see Figure 63).

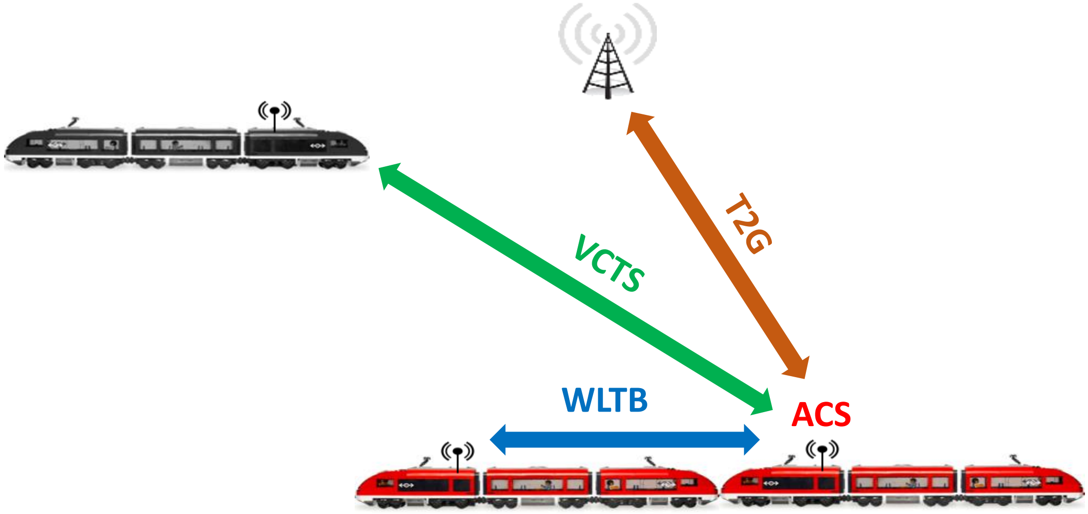


Figure 63. Integration of WLTB, VCTS and T2G links

However, communication distances for VCTS can be much longer than those for WLTB or T2G, so the possibility of using the same radio technology to cover these three domains might not always be feasible; it could be considered for example in urban applications (e.g. trams and metros), where smaller communication distances are required for VCTS. Another possibility to cover long distances with the same radio technology would be to use VCTS based on an infrastructure, therefore combining T2G and G2T links to cover the full VCTS link. However, this would add additional latencies that might not be acceptable for certain VCTS applications.

Related to this point, Table 13 shows the wireless technologies considered for the WLTB in CONNECTA-2/Safe4RAIL-2. As can be observed, the range of these technologies is below 1km. Future technologies, such as IEEE 802.11bd and NR-V2X, are expected to operate in the same range.

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

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

Table 13. Wireless technologies for WLTB

The communication ranges shown in Table 13 are estimated values for the most usual operational environments of these technologies. We can obtain more realistic values for T2T links using the path-loss models from Roll2Rail project, included in public deliverable D2.2:

- Attenuation (Tunnel) = $14.5 \cdot \log_{10}[d(m)] + 54.8$ (dB)
- Attenuation (Station) = $16.4 \cdot \log_{10}[d(m)] + 47.8$ (dB)
- Attenuation (Open-Field) = $15.1 \cdot \log_{10}[d(m)] + 59.9$ (dB)

These models have been obtained at 2.6 GHz for three different propagation environments: station, tunnel and open field. Figure 64, Figure 65 and Figure 66 show the attenuation (i.e. path loss) calculated with these models, and extrapolated at three characteristic cellular and V2X communication frequencies: 700 MHz, 2.6 GHz and 5.9 GHz.

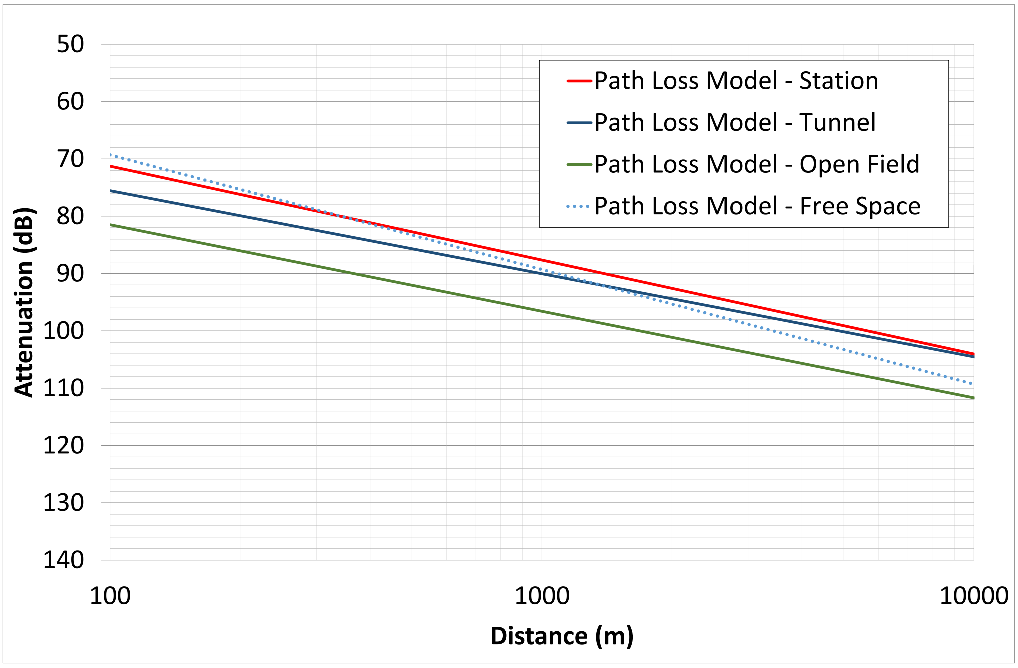


Figure 64. Path loss for a T2T link @700 MHz

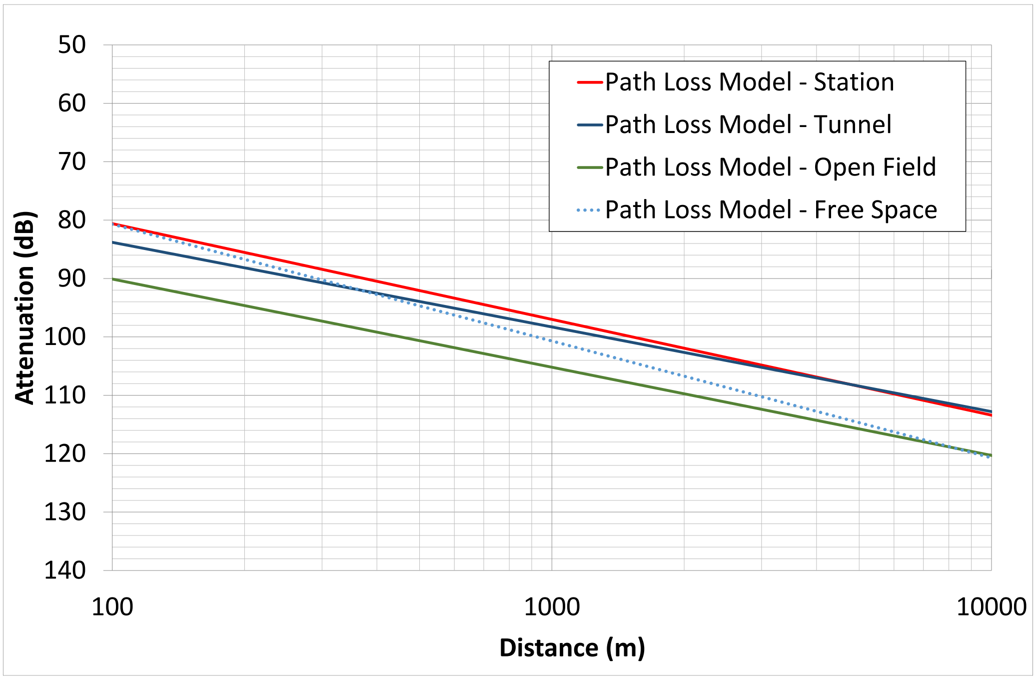


Figure 65. Path loss for a T2T link @2.6 GHz

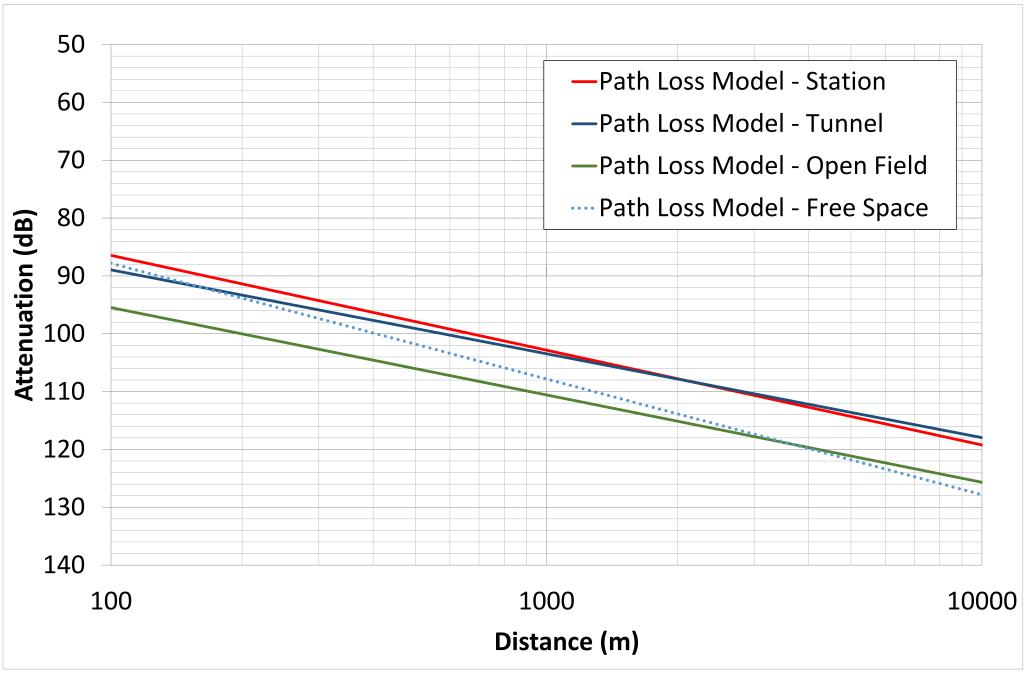


Figure 66. Path loss for a T2T link @5.9 GHz

In order to calculate the maximum operating distance for a link based on LTE-V2X, such as that used in the WLTB, we can make the following assumptions:

- UE Transmitted power = 23 dBm
- UE Antenna gain = 0 dBi (omnidirectional antenna)
- UE Receiver sensitivity = -100 dBm
- Fading margin = 20 dB

These values indicate an available dynamic range of approximately 100 dB for the attenuation of the wireless link. Considering the graphs presented earlier, this indicates a maximum communication distance of 500-1000m, which confirms the theoretical values coming from the state of the art review. Therefore, LTE-V2X technology could only be applied for T2T communications in that range of distances, and that is why a mesh topology with multihop forwarding has been selected as wireless architecture in order to cover a maximum train length of 860m. In order to cover longer T2T links for VCTS, a different wireless technology with higher communication range would need to be selected.

Chapter 6 Summary and Conclusion

In this deliverable several advanced technologies have been considered and analyzed for their integration in wireless TCMS. From these analyses, the following conclusions can be obtained:

1. WLTB and T2G links can be integrated in the ACS device using OAI technology. Two technical approaches have been presented for this integration.
2. Different options have been analysed for the integration of TSN technology in 5G links, as an enabler for the extension of the Drive-by-Data concept to the WLTB.
3. Several analyses have been made for the use of 4G and 5G technology in the WLTB and the WLCN. Obtained results indicate that 4G is not a suitable technology for either WLTB or WLCN. However, these results prove the feasibility of 5G for carrying the required throughput for TCMS traffic, while some limitations are shown for OMTS traffic. Limitations are also found due to the performance of the scheduler in 4G-V2X and 5G-V2X. Further analyses should be carried out with scenarios which are more realistic or more tailored to real-life wireless TCMS applications.
4. The use of WLTB for Virtual Coupling applications has also been analyzed. The conclusions of this study indicate that the WLTB could only be applied for Virtual Coupling with a maximum communication distance of 500-1000m. In order to cover longer T2T links for VCTS, a different wireless technology with higher communication range would need to be used.

As a summary, it can be concluded that the solution for wireless TCMS obtained in Safe4RAIL-2 has several possibilities for extension and improvement taking advantage of different novel wireless technologies.

List of Abbreviations

Table 14: List of Abbreviations

Abbreviation	Explanation
ACK	Acknowledgment
ACS	Adaptable Communication System
AETBN	Adapted ETBN
AF	Application Function
AGC	Automatic Gain Control
AMF	Access and Mobility Management Function
ARP	Allocation and Retention Priority
BE	Best Effort
BMCA	Best Master Clock Algorithm
BS	Base Station
BW	Bandwidth
CF	Correction Field
CN	Consist Network
CNC	Centralized Network Configuration
CSI	Channel Status Information
CTA	CONNECTA
CTA-2	CONNECTA-2
CUC	Centralized User Configuration
D2D	Device to Device
DbD	Drive-by-Data
DL	Downlink
DMRS	Demodulation Reference Signals
DS	Device Side
E2E	End to End
eMBB	enhanced Mobile Broadband
ETBN	Ethernet Train Backbone Node
FDD	Frequency Division Duplex
FIFO	First In First Out

Abbreviation	Explanation
FR	Frequency Range
GCL	Gate Control List
GM	Grand Master
HARQ	Hybrid Automatic Request
HSR	High-availability Seamless Redundancy
ID	Identification
IEEE	Institute of Electrical and Electronics Engineers
IIC	Industrial Internet Consortium
IP	Internet Protocol
ISM	Industrial, Scientific and Medical
ITU	International Telecommunication Union
LBT	Listen Before Talk
LTE	Long Term Evolution
MCS	Modulation and Coding Scheme
MD	Message Data
MIMO	Multiple Input Multiple Output
NACK	Negative Acknowledgment
NR	New Radio
NW	Network
OAI	Open Air Interface
OFDM	Orthogonal Frequency Division Multiplexing
OMTS	On-Board Multimedia and Telematic Services
PCF	Policy Charging Function
PCP	Parallel Redundancy Protocol
PD	Process Data
PDR	Packet Delivery Ratio
PDSCH	Physical Downlink Shared Channel
PDU	Protocol Data Unit
PL	Priority Level
PRACH	Physical Random Access Channel
PRB	Physical Resource Block

Abbreviation	Explanation
PSCCH	Physical SideLink Control Channel
PSFCH	Physical Sidelink Feedback Channel
PSSCH	Physical SideLink Shared Channel
PTP	Precision Time Protocol
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RB	Resource Blocks
RD	Radio Device
RE	Resource Elements
RF	Radiofrequency
RRC	Radio Resource Control
RT	Real Time
SCI	Sidelink Control Information
SCS	SubCarrier Spacing
SD	Supervisory Data
SDU	Service Data Unit
SH-STDMA	Selective Hiding Self-organized Time Division Multiple Access
SIB	System Information Block
SL	Sidelink
SMF	Session Management Function
SP	Semi-Persistent
SPS	Semi-Persistent Scheduler
SRP	Stream Reservation Protocol
SRS	Sounding Reference Signal
SSB	Synchronization Signal Block
STDMA	Self-organized Time-Division Multiple Access
T2G	Train to Ground
T2T	Train to Train

Abbreviation	Explanation
TAS	Time-Aware Shaper
TCMS	Train Control and Monitoring System
TDD	Time Division Duplex
TDMA	Time-Division Multiple Access
TR	Technical Report
TRL	Technology Readiness Level
TS	Technical Specification
TSN	Time Sensitive Networking
TTI	Transmission Time Interval
TX	Transmission
UDM	Unified Data Management
UDP	User Data Protocol
UE	User Equipment
UL	Uplink
UNI	User Network Interface
UPF	User Plane Function
URLLC	Ultra-Reliable and Low Latency Communication
USRP	Universal Software Radio Peripheral
V2X	Vehicle-to-Everything
VCTS	Virtually Coupled Train Sets
WLCN	Wireless Consist Network
WLTB	Wireless Train Backbone
WLTBN	Wireless Train Backbone Node

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Chapter 7 Annexes

7.1 TSN Requirements for Adapted-ETBN

Req ID	Description	Prod.	Dem.	Notes
CTA2-D1.1-1803	The WLTB radio device shall be able to propagate clock synchronization to the ECN via IEEE 1588 with a precision of ≤ 10 µs with a jitter of ± 1 µs (consist level) of ≤ 20 µs with a jitter of ± 2 µs (train level)	*Requires further analysis*		
DBD_ND_003	The ND shall support clock synchronization in accordance to IEEE 802.1AS-2020	*Requires further analysis*		
DBD_ND_004	The ETBN shall provide master clock for train (GlobalMC) and for ECN (ConsistMC)	*N*		
DBD_ND_005	The ETBN shall provide gateway functionality for TSN and time information	*N*		
DBD_ND_010	The ETBN shall support scheduled traffic in accordance to IEEE 802.1Qbv	*N*		If they are synchronized, they should use Qbv
DBD_ND_011	The ETBN shall support per stream filtering and policing as defined in IEEE 802.1Qci	*N*		
DBD_ND_101	The network shall forward the timing information coming from world clock or system time generator to the end devices.	*Y*		LTE modules have their own synchronization mechanisms. However, it needs to be checked if they are able to share it using IEEE 802.1AS or IEEE 1588.
DBD_ND_102	Upon unrecoverable loss of synchronization, the ETBN shall stop synchronous time-aware operations.	*N*		
DBD_ND_103	The ETBN shall be a time-aware device as defined in 802.1AS-2020.	*N*		
DBD_ND_104	The ETBN shall include a precise clock which can be configured as GMC	*Y*		LTE modules get GMC from GPS or some other source (e.g. base station, or master UE in D2D)
DBD_ND_105	Master clock drift shall be <2ppm per second.	*Y (the specific drift value requires further analysis)*		The phase drift could also be an issue
DBD_ND_106	ETBN shall synchronize by using redundant time information from multiple clock domains.	*Y*		
DBD_ND_107	Device synchronization configuration shall enable synchronization to clock domains from only one train synchronization domain.	*N*		
DBD_ND_108	ETBN clocks in the first and the last consist on both communication lines shall act as GMCs.	*N*		

Req ID	Description	Prod.	Dem.	Notes
DBD_ND_109	ETB grandmasters clock (GMC) shall provide time information to the configured synchronization domain.	*N*		
DBD_ND_111	ETBN switch shall police all synchronization packets.	*N*		
DBD_ND_114	ETB GMC shall send time information on a dedicated stream (traffic class) according to its priority and topology position.	*N*		
DBD_ND_115	The priority of each GMC shall have values 0<priority<7.	*N*		
DBD_ND_116	Each GMC shall have a unique priority within its synchronization domain.	*N*		
DBD_ND_117	A grandmaster clock (GMC) shall disseminate time information by using IEEE 802.1AS-2020 messages.	*N*		
DBD_ND_118	GMCs shall send clock information using Sync packets at defined time instants, within the Sync packet transmission period. Note: This applies after synchronous startup for all GMCs.	*N*		
DBD_ND_119	GMC shall monitor Sync packet order and arrival time.	*N*		
DBD_ND_120	Configuration of GMCs and network shall ensure that all Sync packets are received at expected order, within a defined period.	*N*		
DBD_ND_121	GMCs shall ignore ANNOUNCE messages and BMCA algorithms.	*N*		
DBD_ND_122	On synchronous startup and if external time reference is available, the highest-priority GMC shall abruptly adjust his clock to the external reference time.	*N*		
DBD_ND_123	On power-up, if an external time reference is not available, the highest priority GMC shall start sending Sync messages with its own RTC as a timebase.	*Requires further analysis*		
DBD_ND_124	The acquired time from an external time reference will be disseminated as a correction factor to the existing system time.	*N*		
DBD_ND_125	During the TCMS grandmasterclock (GMC) synchronization startup, the higher priority GMCs shall supply its own timebase (local clock) to the lower priority GMCs.	*N*		The average of 4 GMCs is used, as defined in S4R-1
DBD_ND_126	During the TCMS grandmasterclock (GMC) synchronization startup, a GMC shall align its time to higher priority GMCs' times within the Sync message period.	*N*		
DBD_ND_127	During the TCMS grandmasterclock (GMC) synchronization startup, in case of abrupt time changes coming from higher priority GMCs lower-priority GMCs shall detect such time changes.	*N*		
DBD_ND_128	During the TCMS grandmasterclock (GMC) synchronization startup, in case of abrupt time changes coming from higher priority GMCs lower-priority	*N*		

Req ID	Description	Prod.	Dem.	Notes
	GMCs shall tolerate time changes if their consecutive number is lower than 2.			
DBD_ND_129	During the TCMS grandmasterclock (GMC) synchronization startup, in case of abrupt time changes coming from higher priority GMCs lower-priority GMCs shall tolerate such abrupt time changes if the number of GMCs on ETB is higher than 2.	*N*		
DBD_ND_130	During the TCMS masterclock (MC) synchronization startup, the lower priority MCs shall ignore higher priority GMCs which over a configured period exhibit implausible behaviour.	*N*		
DBD_ND_131	TCMS grandmaster clock (GMC) synchronization startup shall initialize after a completed topology discovery as part of the inauguration procedure.	*Under definition by CTA-2*		
DBD_ND_132	ETBN shall begin synchronization after successful TCMS grandmaster clock (GMC) synchronization startup.	*Y*		
DBD_ND_133	ETB GMC from the last ETBN in topology shall synchronize to the ETB GMC in the 1st ETBN on both communication lines after 1st train power-up and completion of ETB inauguration.	*Under definition by CTA-2*		
DBD_ND_134	After completed synchronous startup, GMC shall obtain information from other GMCs on its own clock quality. Note: independent external monitoring.	*Requires further analysis*		
DBD_ND_135	An ETBN shall synchronously start-up within a predefined maximum period of time.	*Requires further analysis*		
DBD_ND_136	GMC shall align their clocks in precision of <=5µs	*Requires further analysis*		
DBD_ND_137	If the time difference is higher than 5µs for more than a defined period of time, then GMC shall go into inactive state until next power-up.	*Requires further analysis*		
DBD_ND_138	If the majority of other GMCs is not aligned with GMC for more than 10 seconds, then GMC shall go into inactive state until next power-up.	*Requires further analysis*		
DBD_ND_139	ETBN shall use time information from gPTP clock domains for fault detection, preselecting correct clocks and tolerating faulty clock sources.	*Y*		
DBD_ND_140	Network devices shall monitor the origin (sender) of gPTP packets using MAC DEST and VLID / streamIDs and priority information.	*Y*		
DBD_ND_141	Synchronization slave devices shall monitor the order of gPTP packets using sequence numbers.	*Y*		
DBD_ND_142	Ordinary clock (OC) slaves shall diagnose and identify correct time by adapting the calculation approach, depending on the number of gPTP clock domains active and available: * For 1 active – take it as is with PDV; * For 2 active – average over two	*Requires further analysis*		

Req ID	Description	Prod.	Dem.	Notes
	values, if within 5microseconds (ECN) or 10 microseconds (ETB), otherwise non-conclusive; * For 3 active - voting 2oo3 voting for 3 clocks, takes 2 clocks which are within 5 microseconds (ECN) or 10 microseconds (ETB), average over 2 correct gPTP instants, otherwise non-conclusive; * For 4 active - discarding the highest and lowest value and averaging over two remaining values assuming their difference is within 5microseconds (ECN) or 10 microseconds (ETB), otherwise non-conclusive.			
DBD_ND_143	The ETBN shall switch to the Inactive Mode, if unable to synchronize to the global GMC time values within the configured grace period (e.g. 1 sec).	*Y*		
DBD_ND_144	The ETBN shall switch from Inactive to the Inauguration Mode upon external request.	*Requires further analysis*		
DBD_ND_145	ETBN shall tolerate link interruptions or failures of up to 1 second, before they are allowed to transfer into inactive mode.	*Y (the specific duration requires further analysis)*		
DBD_ND_146	The ETBN shall continue synchronous (GCL list) operation using the local clock time within a configured grace period. (e.g. at least 1sec), if there is no reliable information to identify correct/valid time sources.	*Requires further analysis*		
DBD_ND_147	ETB configuration shall define a standardized number of streams for transmission to the 1st and last consist, and from/to ECN, depending on its topology position.	*Requires further analysis*		
DBD_ND_277	The Network Device shall police all critical multi-cast messages using the same configuration data for traffic from left (toward leading car) and right (opposite from leading car) side.	*Requires further analysis*		
DBD_ND_278	The Network Device shall police and forward multi-cast message which are specified only for its topology position.	*Requires further analysis*		
DBD_ND_279	The Network Device shall contain a stream filter table in which the filtering and policing actions per stream filter are defined.	*N*		
DBD_ND_280	The Network Device shall contain a stream gates table in which the opening and closing states and events per stream gate are defined.	*Requires further analysis*		
DBD_ND_281	The stream gates table shall contain a stream gate control list for ingress traffic.	*Requires further analysis*		
DBD_ND_282	The Network Device shall contain flow meters instance table in which flow parameters are defined.	*Requires further analysis*		
DBD_ND_283	The Network Device shall use the time information from valid and correct gPTP	*N*		

Req ID	Description	Prod.	Dem.	Notes
	clock domains to align the cyclic operation of IEEE TSN Gate Control Lists (GCL).			
DBD_ND_284	The ETBN shall police and prevent synchronization SYNC traffic from any ECN, not being the consist 1 or last consist.	*N*		
DBD_ND_288	Network Device shall support time-driven packet switching and forwarding (802.1Qbv) with capability to send packets in a defined time period.	*Requires further analysis*		
DBD_ND_290	Network Device shall have a gate control list (GCL) for every egress port that defines gate operations.	*Requires further analysis*		
DBD_ND_291	Each GCL shall allow at least 64 entries.	*Requires further analysis*		
DBD_ND_292	Network Device shall initiate the execution of the gate control list at startup.	*Requires further analysis*		
DBD_ND_293	Network Device shall ensure that the gating cycle time defined for the port is maintained	*Requires further analysis*		
DBD_ND_294	Network Device shall execute the gate operations in the gate control list, in sequence	*Requires further analysis*		
DBD_ND_295	Network Device shall establish the appropriate time delay between each operation	*Requires further analysis*		
DBD_ND_351	TSNGW shall collect and store all system-relevant time-sensitive (or critical) traffic from ECNs.	*Under definition by CTA-2/S4R-2*		
DBD_ND_352	TSNGW shall collect and periodically disseminate incoming train-relevant data from other TSNGWs to its local ECN, and vice versa.	*Under definition by CTA-2/S4R-2*		
DBD_ND_353	TSNGW shall periodically/deterministically disseminate system-relevant data in line with schedule.	*Under definition by CTA-2/S4R-2*		
DBD_ND_354	TSNGW shall send only to configured stream identifiers, with configured timing and periodicity depending on its position in the topology.	*Under definition by CTA-2/S4R-2*		
DBD_ND_355	TSNGW shall collect all the train-relevant data in datasets multicast from other ETB switches for forwarding to its connected ECN nodes.	*Under definition by CTA-2/S4R-2*		
DBD_ND_356	GCL list period for gate control shall be configurable at least 2.5ms	*Under definition by CTA-2/S4R-2*		
DBD_ND_357	TSNGW shall inspect and store received ECN packets which contain system-relevant data and match configured packet header identifiers (e.g. MAC SRC/DEST, VLID, …).	*Under definition by CTA-2/S4R-2*		
DBD_ND_358	TSNGW shall inspect and forward received ECN packets to ETBN, only if they match the configured packet headers.	*Under definition by CTA-2/S4R-2*		

Req ID	Description	Prod.	Dem.	Notes
DBD_ND_359	TSNGW shall inspect and forward received ETB packets to ECN network, only if they match the configured packet headers.	*Under definition by CTA-2/S4R-2*		
DBD_ND_360	TSNGW shall disassemble ECN packet data with application CRC according to configuration.	*Under definition by CTA-2/S4R-2*		
DBD_ND_361	TSNGW shall assemble datasets, consisting of at least one ECN packet data.	*Under definition by CTA-2/S4R-2*		
DBD_ND_362	With each piece of data assembled, the data freshness timer (system time stamp) will be stored.	*Under definition by CTA-2/S4R-2*		
DBD_ND_363	Only provably correct data (CRC, bitwise comparison, redundant data etc.) shall be used for the assembly of datasets. Note: for invalid data will not be stored and data freshness will not be updated, therefore the last generation of data will be used.	*Under definition by CTA-2/S4R-2*		
DBD_ND_365	TSNGW shall store the complete constructed dataset into configured ETB_SHMEM_POSITION(n). Note: n = constant sampling memory position defined by configuration data.	*Under definition by CTA-2/S4R-2*		
DBD_ND_366	For each ECN packet sent to ECN, and assembled from ETB_SHMEM data, TSNGW configuration shall define for each data piece, the source of the dataset (ETB_SHMEM _POSITION(n)),its exact position in the dataset, and data length.	*Under definition by CTA-2/S4R-2*		
DBD_ND_367	Configuration Parameters: For each dataset parameter or variable, the TSNGW configuration shall define: the source of the ECN data (packet header identifiers, MAC SRC/DEST) and its length (LEN) and position (FR_POS) in the frame.	*Under definition by CTA-2/S4R-2*		
DBD_ND_368	TSNGW shall send datasets from “ETB SHMEM” at configured time instants by using a predefined data stream packet identifier (SRC MAC, DEST MAC, VLAN ID/priority, IP Address, UPD port)	*Under definition by CTA-2/S4R-2*		
DBD_ND_369	A dataset from “ETB SHMEM”, the TSN packet shall multicast to all other ETBNs, when an interval/period timer indicates the time is ready for transmitting at least one packet associated with this periods, as defined by configuration.	*Under definition by CTA-2/S4R-2*		
DBD_ND_370	TSNGW shall provide configuration (5) for mapping of ECN packet data to ETB datasets	*Under definition by CTA-2/S4R-2*		
DBD_ND_371	TSNGW shall provide configuration (6) for periodic sending of the consist’s own ETB datasets.	*Under definition by CTA-2/S4R-2*		

Req ID	Description	Prod.	Dem.	Notes
DBD_ND_372	TSNGW shall provide configuration (2,3) for mapping of ETB datasets data to ECN packets.	*Under definition by CTA-2/S4R-2*		
DBD_ND_373	TSNGW shall provide configuration (4) for periodic sending of consist's own ETB datasets.	*Under definition by CTA-2/S4R-2*		
DBD_ND_374	TSNGW shall periodically collect and store its own ETB switch health status including port error statistics from MIB list: • For left and right ETB port • for ETB to ECN port • for ETB to TSNGW port	*Under definition by CTA-2/S4R-2*		
DBD_ND_375	TSNGW shall collect and store its own ETB switch current state (synchronous, asynchronous, …), as they occur (event-driven).	*Under definition by CTA-2/S4R-2*		
DBD_ND_376	TSNGW shall periodically collect and store gPTP synchronization information and history from at least one second (100x).	*Under definition by CTA-2/S4R-2*		
DBD_ND_377	TSNGW health status and/or synchronization history, or their constituents shall be disseminated via ETB to other consists periodically, if configured.	*Under definition by CTA-2/S4R-2*		
DBD_ND_378	TSNGW health status and/or synchronization history, or their constituents shall be disseminated to ECN on request.	*Under definition by CTA-2/S4R-2*		
DBD_ND_401	NG TCN shall transfer TSN data between ECNs on both ETB lines in redundant data streams.	*Y*		
DBD_ND_402	The Network Device shall support the forwarding of frames duplicated according to 802.1CB FRER	*Y*		
DBD_ND_403	The Network Device shall be able to remove R-TAG from incoming frames	*Y*		
DBD_ND_404	The Network Device shall re-insert R-TAG into outgoing frames if they carried R-TAG on ingress (unrecognized/unconfigured streams).	*Y*		
DBD_ND_655	TSN Gateway settings: Scheduled data streams must be predefined according to application specific requirements.	*N*		
DBD_ND_656	TSNGW: When the gateway is located within the ETBN, the configuration for ETB/ECN data mapping and the configuration of the ETB/ECN scheduled data shall be set.	*N*		

7.2 Annex: WLTB and WLCN Traffic analysis

Table 15 shows the traffic requirements defined by CONNECTA-2 for the backbone. This traffic has been split into TCMS (Train Control and Monitoring System) and OMTS (On-Board Multimedia and Telematics Services), and classified as periodic and aperiodic.

	TCMS				**OMTS**		
	Process Data		**Message Data**	**Supervisory Data**	**Streaming**		**Best Effort**
	Time Sensitive	***Normal***			***Audio***	***Video***	
Data Size (bytes)	1432	1432	65388	1500	N/A	N/A	4GB
Cycle time (ms)	1	10	N/A	50	N/A	N/A	N/A
Data Rate (Mbps)	100	100	10	10	3.2	256	≥ 10
Latency (ms)	16	32	500	16	100	100	N/A
	Periodic		***Aperiodic***	***Periodic***	***Aperiodic***		

Table 15. CTA-2 traffic performance values. Inter consist (WLTB)

It must be noted that even though WLTB and WLCN traffic have different latency requirements, the same analysis applies in order to obtain TCMS and OMTS packet size in terms of highest traffic load.

7.2.1 *TCMS traffic*

TCMS traffic demanded over time (divided into subframes of 1 msec) is plotted in Figure 67, divided into:

- *Periodic traffic:* Process Data (time sensitive, normal) and Supervisory Data, which are deterministic according to their cycle time (1ms for Time Sensitive PD, 10 ms for Normal PD, and 50 ms for Supervisory Data).
- *Aperiodic traffic:* message data, which is non-deterministic.

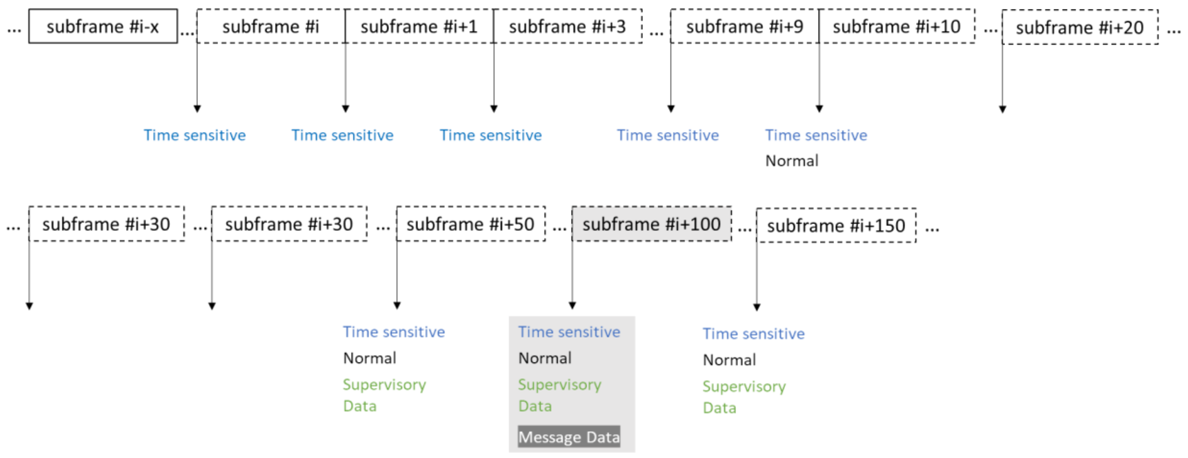

Figure 67 TCMS traffic over time

The highest traffic load (i.e. worst-case scenario) will occur when both periodic (Process Data and Supervisory Data) and aperiodic traffic (Message Data) are ready to be transmitted in the same subframe (e.g., subframe #i+100 in Figure 67). Ideally, the total bits transmitted during this subframe would be calculated as follow:

$$total\ bits\ in\ 1\ subframe\ =\ TimeSensitive\ +\ Normal\ +\ Message\ Data\ +\ Supervisory\ Data$$

$$total\ bits\ in\ 1\ subframe\ =\ 8\ *\ (\ 1432\ +\ 1432\ +\ 65388\ +1500)\ =\ 558016\ bits$$

560kbit per subframe is a non-realistic value for 4G-LTE, where the maximum resources elements (REs) available are 16800 (14*12*100). Without considering that some of them must be booked for signal references, and supposing a modulation order of 6 and a coding rate of 0.5, this value implies 50kbits per subframe. Similarly, 5G-NR cannot cover this payload size in a realistic scenario. For FR2 (Frequency Range 2, above 24GHz) the maximum REs are 354916 (2^3*12*264*14); with a coding rate of 0.5 and a modulation order of 6, it implies 1000 kbits per subframe. For FR1 (Frequency Range 1, below 7 GHz), it implies 91728 REs (2^1*12*273*14) which corresponds to 275 kbits per subframe. All in all, packet size and traffic issue must be addressed in order to find a feasible solution. To do that, the following procedures and assumptions have been considered:

1. An extra of ten bytes has been added to every packet because of the header from 4G-LTE or 5G-NR upper layers (PDCP: Packet Data Convergence Protocol, RLC: Radio Link Control, MAC: Medium Access Control). This value is not fixed and depends on upper layer configurations; however, ten bytes are considered as representative for this analysis.
2. For Periodic Traffic:
    - Time sensitive bits must be fully transmitted because of its cycle time (1 ms) in the current subframe: (header + payload) * 8

$$bits_{1\ subframe}^{time\ sensitive} = (10 + 1432) * 8 = 11536\ bits$$

    - Normal and Supervisory Data are transmitted over their cycle time; therefore, in the current subframe it is transmitted the proportional payload from the total size: (header + proportional payload) * 8

$$bits_{1\ subframe}^{Normal} = \left(10 + \frac{1432}{10}\right) * 8 = 1226\ bits$$

$$bits_{1\ subframe}^{Supervisory\ Data} = \left(10 + \frac{1500}{50}\right) * 8 = 320\ bits$$

3. For Aperiodic Traffic:
    - It is transmitted at its maximum data rate during the subframe

$$bits_{1\ subframe}^{Message\ Data} = 10\ *\ 8\ +\ \frac{10 * 10^6 * 10^{-3}}{1} =\ 10080\ bits$$

Following this procedure, it is assumed that periodic traffic is completely transmitted before cycle times are expired. It means that periodic traffic is guaranteed in every subframe and aperiodic traffic is transmitted at its maximum rate. In Table 16 it is specified the TCMS total traffic per node.

TCMS packet size (Bits per ms)				
Process Data		**Message Data**	**Supervisory Data**	**TOTAL**
Time Sensitive	***Normal***			
11536	1226	10080	320	**23162**

Table 16 TCMS packet size

7.2.2 OMTS traffic

OMTS traffic only carries aperiodic traffic (see Table 15). Therefore, in order to obtain the packet size, an similar analysis as for TCMS Message Data is carried out, obtaining the results shown in Table 17.

OMTS packet size (Bits per ms)			
Streaming		**Best Effort**	**TOTAL**
Audio	**Video**		
3280	256080	10080	**269440**

Table 17 OMTS packet size

7.3 Annex: 5G femtocells range analysis

Regarding commercial femtocell solutions, Ericsson presents 5G Radio Dot [29],[30], which will be an evolution of its current LTE indoor solution, and Nokia has its dual smart node (Smart Node 4G+5G Multi-standard) [31]. From literature [32], the following cell radius values are obtained (see Table 18).

Cell Type	Typical Cell Radius	PA Power: Range & (Typical Value)
Macro	>1 km	20W - 160W (40W)
Micro	250m - 1 km	2W - 20W (5W)
Pico	100m - 300m	250mW - 2W
Femto	10m - 50m	10mW - 200mW

Table 18 Different cell radii and TX power levels [32]

However, it must be taken into account that cell radius depends on factors such as environmental conditions, frequency band, transmission power level, etc. Because of that, a further analysis is developed here in order to provide a first approach about the range that can be achieved with 5G femtocells. A setup is considered where a femtocell provides services to a group of UEs forming a cluster (e.g. a femtocell in a train-car, see Figure 68). The maximum distance between the femtocell base station and UEs (i.e. cell range) will be determined by the transmitted power of the base station, path loss and UE sensitivity, which is the minimum power level that an UE needs to guarantee a specific bit error rate value.

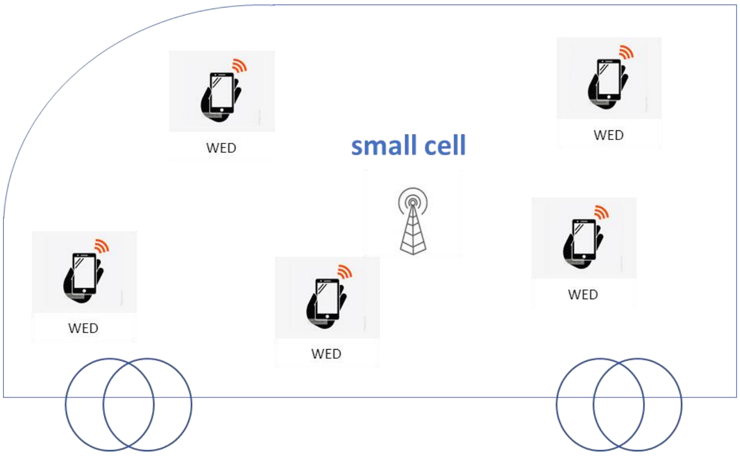

Figure 68 Femtocell in a train-car

The communication link inside the femtocell can be described by Friis equation:

$$P_{RX\ (UE)} = P_{TX\ (Femtocell)} - L_{Path-Loss}(f, d) - FM$$

$$Friis'\ eq \rightarrow P_{RX} = \frac{P_{TX} * \lambda^2}{(4\pi R)^2}$$

where path loss depends on the frequency band and the distance (supposing a transmission through the free space). Fading Margin (FM) parameter, which is the most dependable on the environment conditions, is a key parameter and also the most difficult one to determine, as it includes fluctuations due to shadowing and small-scale fading. A minimum FM value of 30 dB can be taken as a recommendation. As an example, in [33] a theorical analysis is done to obtain a reasonable FM value for outdoor environments, focusing this analysis on climatic and meteorological factors. Considering this factor, the minimum received signal received (i.e. receiver sensitivity) can be modelled as:

$$P_{RX\,(UE)}(dBm) = P_{TX\,(Femtocell)}(dBm)\ -20\ *\log(\frac{4\pi * d * f}{c})\ -\ FM\,(dB)$$

$$S(dBm) \geq P_{TX\,(Femtocell)}(dBm)\ -92.44\ -\ 20 * \log d\,(km) -\ 20 * \log f\,(GHz)\ -\ FM\,(dB)$$

Extracting the distance value (“d”) from this equation, we can obtain the cell range in terms of frequency, transmission power and fading margin. From Table 18 we can select a transmission power between 10 and 200 mWatts, which can be mapped as power class 3 (23 dBm from the 3GPP technical specification, TS 166 101). Similarly, receiver sensitivity is obtained from the UE specification in 3GPP (i.e. -90,-100 dBm). Lastly, 5G NR has two frequency bands defined: FR1 (0.4-7.1 GHz) and FR2 (24.25 – 52.6 GHz).

$$d\,(km) \leq 10^{\left(\frac{P_{TX\,(Femtocell)}(dBm)\ -92.44\ -\ 20*\log f\,(GHz)\ -\ FM\ -\ S\,(dBm)}{20}\right)}$$

In Figure 69 the cell range evolution can be observed for each frequency range (FR1 plotted in green and FR2 plotted in blue), and for the parameters specified. From there, we can confirm that in FR1 frequency band a whole train consist could be covered with one femtocell. However, the higher the frequency the less the range will be; therefore, the coverage in millimetre waves (FR2) could be an issue to overcome.

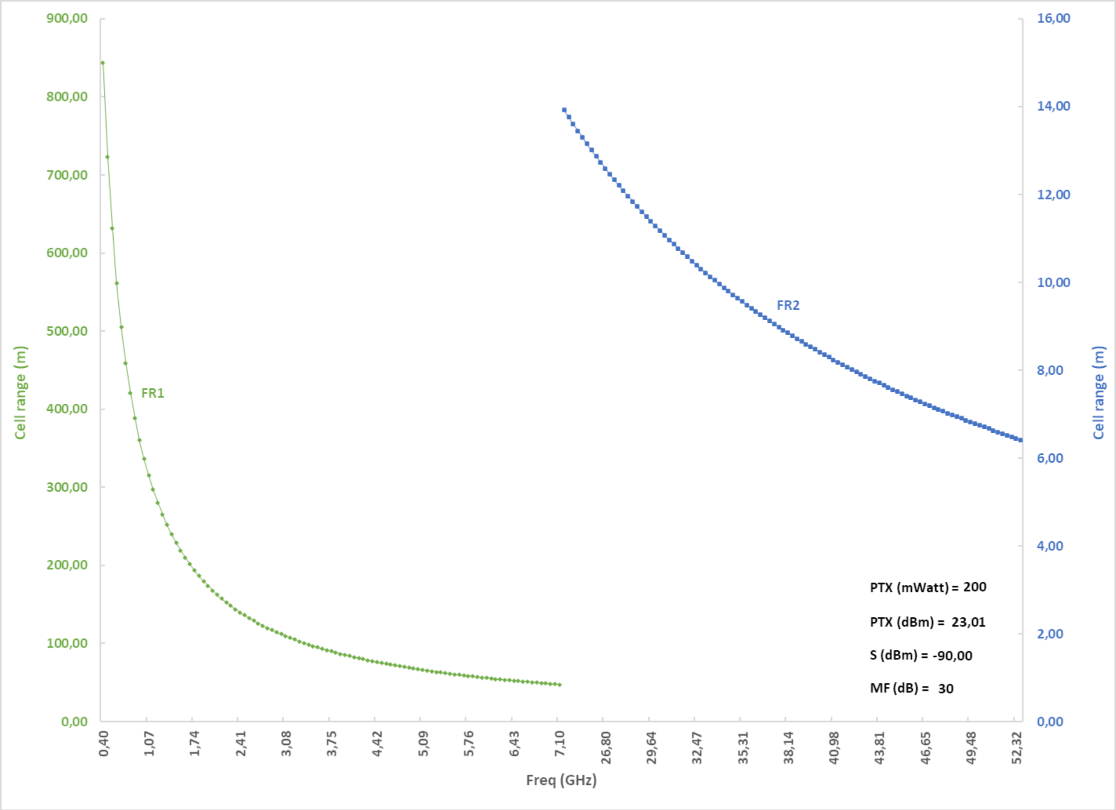

Figure 69 5G Femtocell. Cell range analysis