

5G Technology for Next-Generation Wireless Consist Networks in Railways

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Abstract. Currently, internal communications in trains are based on wired networks to provide Ultra-reliable Low Latency Communications (URLLC) for control and monitoring systems. However, these wired infrastructures are expensive to implement and maintain. Wireless Consist Networks (WLCN) can be a solution to this problem. Particularly, 5th Generation (5G) networks are considered one of the best options to support URLLC. This paper analyzes the use of 5G technology for a Wireless Consist Network (WLCN), as a replacement for the current wired network inside train consists. The goal of this analysis is to calculate which 5G configurations are capable of supporting the worst case of the required train backbone traffic. Obtained results indicate that 5G is a potential technology for sensor and end devices communication in the WLCN.

Keywords: 5G · Wireless · Consist · Railway

1 Introduction

CONNECTA-2 and Safe4RAIL-2 projects are researching on the use of wireless communications for the Next-Generation Train Control and Monitoring System (NG-TCMS). These projects belong to the Shift2Rail initiative of Horizon 2020, which aims at providing novel capabilities for railway industry through research and innovation, as stems out of its Multi Annual Action Plan [1].

The migration of the current wired Train Control and Monitoring System (TCMS) to a wireless architecture is one of the identified areas of opportunities that need to be tackled in the upcoming years. The TCMS is a communication bus that operates in a two-level network architecture: a Train Backbone (TB), which connects different consists or group of vehicles, and Consist Networks (CNs), which are individual networks located inside each consist. The NG-TCMS will apply wireless technologies at both backbone and consist levels, thus creating WireLess Train Backbone (WLTB)

and WireLess Consist Network (WLCN) solutions, which will increase the flexibility, ease interoperability, and reduce the cost of the currently wired solution [2]. In a previous work a preliminary analysis was done for selecting wireless technologies to implement a WLCN [3]. This analysis concluded that no wireless technology currently available was capable of covering all NG-TCMS requirements for the WLCN. For that reason, the capabilities of 5G are explored in this work. A similar analysis was also done for the WLTB in a previous work [4].

The rest of the paper is organized as follows: Sect. 2 and Sect. 3 describe the railway and 5G networks. Section 4 and Sect. 5 explain the proposed wireless consists network architecture and the traffic requirements of end devices and sensors. Section 6 presents the analysis and the results of 5G technology for WLCN. Finally, Sect. 7 presents the conclusions of the presented work.

2 Railway Networking

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

2.1 Train Control and Monitoring System (TCMS)

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

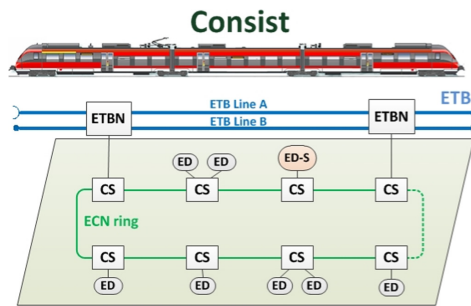


Fig. 1. Example of a simple train communication network (TCN) [3].

2.2 Ethernet Train Backbone (ETB)

Two technologies are covered by IEC 61375 series for Train Backbone: the Wire Train Bus (WTB) and the Ethernet Train Backbone (ETB). The WTB provides deterministic

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

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

2.3 Ethernet Consist Network (ECN)

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

2.4 Wireless Railway Networking Challenges

One major innovation targeted for NG-TCMS is to replace wired parts of the railway vehicles by wireless technologies, with the objective to reduce cost, enhance maintenance and diagnosis as well as enable innovative applications such as wireless drive-by-wire or virtual coupling and train platoons. In this paper, we focus on the WLCN. Many challenges lie ahead, such as uncontrolled interferences, unreliable wireless links, unstable capacity and delay, not mentioning cyber-security.

3 5G Networks

5th Generation mobile network (5G) has been designed in order to support several vertical domains such as transport, health and manufacturing. 5G supports massive amounts of devices (Massive Machine Type Communication, mMTC), provides increased data rates (Enhanced Mobile Broadband, eMBB) and guarantees high reliability and low latency requirements (Ultra-Reliable and Low-Latency Communications,

URLLC). 5G has two fundamental parts which are the Radio Access Network (RAN) and the Core Network (CN). The UE (User Equipment) and the gNB (new generation Node B), the user and the base station respectively, are located within the RAN [5].

In 5G, a frame lasts 10 ms and it is composed of subframes with 1 ms duration (Fig. 2(a)). A subframe contains different number of slots. 5G supports different numerologies, which is the spacing between sub-carriers (SCS). The SCS goes from 15 kHz to 240 kHz, so the slot duration goes from 1 to 0.0625 ms. In addition, each slot has 14 symbols, except in the case of extended preamble which contains 12 symbols. The resource grid is characterized by one subframe in time domain and full carrier bandwidth in the frequency domain (Fig. 2(b)). There is one resource grid for each transmission direction (downlink (DL) or uplink (UL)), antenna port and sub-carrier spacing configuration. The carried bandwidth can be divided into Resource Blocks (RB). One RB has 12 subcarriers, whereas 1 subframe has 14 OFDM symbols \times n° slots in a subframe OFDM symbols. A resource element (RE) is composed by one OFDM symbol in the time domain and one subcarrier in the frequency domain.

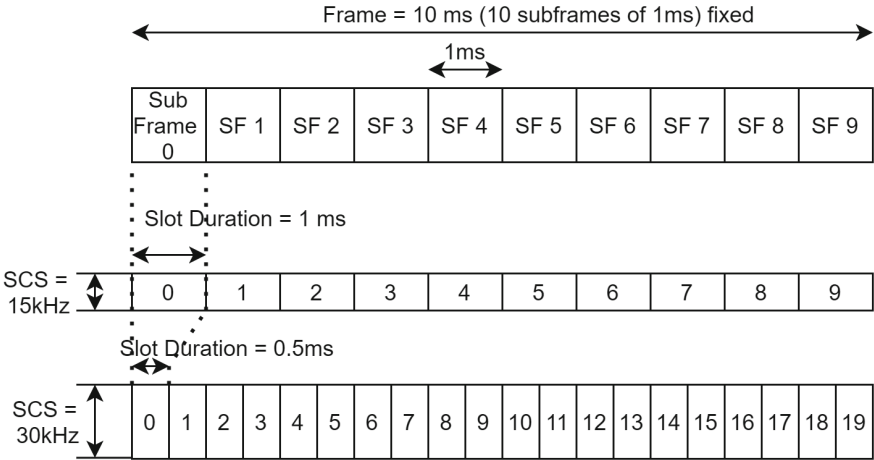


Fig. 2. 5G frame structure for SCS of 15 kHz and 30 kHz (a), and 5G resource grid for SCS of 15 kHz (b).

The resource elements can carry user data and control data. The DL control REs are Synchronization Signal Block (SSB), which is used for cell search, so the UEs acquires time and frequency synchronization with a cell and Channel Status Information (CSI) which is a mechanism used by the UEs to measure the quality of the radio channel and report the results to the gNB. Furthermore, Physical Downlink Shared Channel (PDSCH) is the physical channel that transmits user data in DL. The Demodulation Reference Signal (DM-RS) and Phase Tracking Reference Signal (PT-RS) are added to PDSCH. These two signals are reference signals and are generated within PDSCH. On the one hand, DM-RS is used to estimate the channel, on the other hand, PT-RS is used to compensate the Common Phase Error (CPE). For UL, Physical Random-Access Channel (PRACH), Sounding Reference Signal (SRS) and CSI are

used as control signals. The PRACH is used by UEs to request an UL allocation from the base station, and it is the first message from UE to gNB. Moreover, Physical Uplink Shared Channel (PUSCH) transmits user data in UL as well as DMRS and PT-RS control signals.

In addition, 5G supports two operating bands [6]: Frequency Range 1 (FR1) frequencies below 7 GHz and Frequency Range 2 (FR2) that represents millimeter waves that are above 24 GHz. In FR1, the widest transmission bandwidth is 100 MHz with a full capacity of 273 RBs with a numerology (μ) of 1. In FR2, the widest transmission bandwidth is 400 MHz which uses 264 RBs with a μ of 3.

4 Proposed Wireless Consist Network Architecture

The WLCN covers the communications inside each consist and towards the WLTB. The main difference with the WLTB lies in the fact that the WLCN requires a higher number of nodes and has to operate in a more complex propagation environment (e.g. reflections on metallic structures and cabinets, influence of passengers, etc.). The Fig. 3 details the architecture proposed by CONNECTA-2 for the WLCN. This architecture is made of two redundant wireless networks, each of them having one Wireless Access Point (WAP) per vehicle. Wireless End Devices (WEDs) are connected to a WAP, except the Safe Wireless End Devices (WED-S), which will be connected to two WAPs for higher reliability, each one from a different wireless network, and therefore will require two wireless interfaces. On the other hand, all WAPs will be connected to Consist Switches (CS), which will be interconnected via a wired Ethernet Consist Network (ECN).

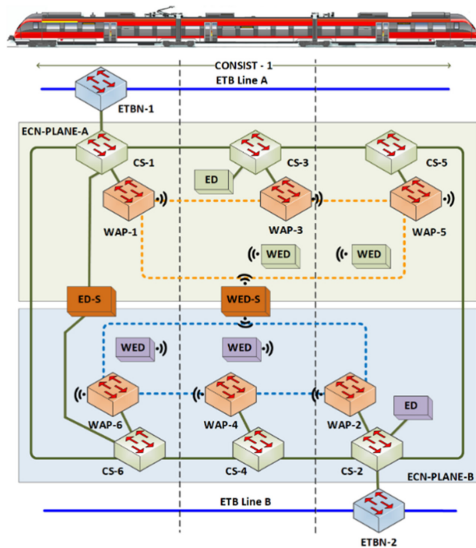


Fig. 3. WLCN architecture.

The previous approach is a suitable solution for the NG-TCN because it simplifies the integration of different wireless technologies, as in the case of 5G. For a 5G implementation, a WAP would be replaced by a gNB, and WEDs would be User Equipment-s (UEs). Figure 4 shows such a deployment, which follows a star topology where a gNB per car acts as a central node which manages the traffic flowing through the UEs. A maximum of 30 UEs are considered per car.

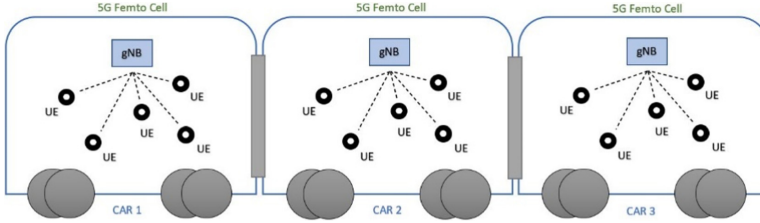


Fig. 4. Infrastructure-based 5G WLCN.

5 Wireless Consist Network (WLCN) Traffic

The requirements for the TCMS traffic of the Next-Generation Consist Network are detailed in Table 1, obtained from CONNECTA D3.1 Deliverable [7]. This traffic represents the typical consist TCMS traffic used in a wired network. The TCMS traffic includes three types of data: Process Data (PD) for small-sized and periodic data, Message Data (MD) which is bigger sized than PD and aperiodic data, and Supervisory Data (SD) which is periodic data used for supervision and for the inauguration process.

Table 1. TCMS Traffic requirements for consist network [7].

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

A worst-case scenario in terms of capacity will occur when all periodic (PD, SD) and aperiodic (MD) messages are sent in the same subframe. This worst-case calculation is summarized in Table 2, where 10 extra bytes have also been added to each traffic as an average payload of the upper layers of 5G. This calculation has been made for the traffic generated by end devices such as Central Control Units (CCUs); in a

consist network there will be also additional devices such as sensors, who will have much lower traffic requirements. For sensors we can assume 100 bytes of Process Data every 1ms; with the addition of the extra bytes for the 5G upper layers, this will imply 880 bits per ms, which is much lower than the value required by end devices. This is also summarized in Table 2.

Table 2. Traffic generated per node (bits per ms).

	PD		MD	SD	Total
	TS	N			
End devices	11536	11536	10080	320	33472
Sensors	880	0	0	0	880

6 Analysis and Results of 5G Technology for WLCN

This section presents a numerical analysis of 5G capacity for a WLCN network. For this purpose, a customized resource-grid has been designed taking into account the control and user REs described in Sect. 3. This resource-grid design adopts the most restrictive configuration regarding the amount of resources occupied by reference signals. The configuration parameters are listed in Table 3.

Table 3. Resource grid: UL (left) and DL (right).

PRACH		SSB	
M (msg1-FSM)	8	Aggregation Level	16
SRS		Corest symbols	3
Symbols per slot	4	CSI	
Density per RB (kTC)	4	Density per RB	1
RBs	264	Slots density	4
CSI		PDSCH	
Density per RB	1	PT-RS RB density	2
Slots density	4	PT-RS time density	1
PUSCH		DMRS time type	A
PT-RS RB density	2	DMRS length	1
PT-RS time density	1	Additional DMRS symbols	0
DMRS time type	A	DMRS freq type	2
DMRS length	2	DMRS freq density	4
Additional DMRS symbols	0		
DMRS freq type	2		
DMRS freq density	4		

Considering the designed resource grid in Table 3, Table 4 indicates the maximum capacity that FR1 and FR2 bands are able to provide for different antenna configurations and Modulation Coding Scheme (MCS) values. To obtain the most restrictive scenario, it is assumed that the periodic and aperiodic data, as well as the control and user data are transmitted in the same subframe. As it is a control and monitoring system deployment, a symmetrical bandwidth division is assumed for UL and DL transmissions. It is further considered that the streams of codeword encodings are mapped directly to RF ports and physical antennas, enabling spatial multiplexing. First, the total number of REs inside a subframe are calculated (Eq. 1):

Table 4. Maximum 5G capacity (Mbps).

		Antennas	MCS index			
			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

$$TotalRE_{persubframe} = RB_{intheBW} \times 2^{\mu} \times 14_{sym} \times 12_{subcarriers} \quad (1)$$

Therefore, the $TotalRE_{persubframe}$, with numerology (μ) 1, is $273 \text{ RBs} \times 2^1 \times 14 \text{ symbols} \times 12 \text{ subcarriers}$ which is equal to 91728 REs and $TotalRE_{persubframe}$, with numerology 3, is $264 \text{ RBs} \times 2^3 \times 14 \text{ symbols} \times 12 \text{ subcarriers}$ which is equal to 354816 RE-s. Then, considering the antenna layers and removing the REs that are used for signalling (Table 3) from the $TotalRE_{persubframe}$, the number of REs for DL or UL that are used for data transmission are obtained (Eq. 2):

$$RE_{PUSCH/PDSCH} = antennaLayers \times \left(\frac{TotalRE_{persubframe}}{2} - RefSignal_{UL/DL} \right) \quad (2)$$

Finally, the maximum 5G capacity is calculated using equation (Eq. 3). To calculate these values, the REs per PUSCH/PDSCH, UL and DL respectively and the MCS of 0, 10, 20 and 28 values [8, table 5.1.3.1-1] are used.

$$Capacity(Mbps)_{max} = \frac{RE_{PUSCH/PDSCH} \times codingRate \times ModulationOrder}{10^6} \times 1000 \quad (3)$$

Required 5G bit rates can be obtained (Eq. 4) for different MCS configurations and for an increasing number of nodes applying the traffic detailed in Table 2 (Eq. 4, totalBits_{1ms}) to this resource-grid. Up to 30 nodes have been considered in this analysis, which is the maximum number of devices per car/femtocell.

$$Capacity(Mbps)_{n^oNodes} = n^oNodes \times \frac{totalBits_{1ms}}{codingRate \times ModulationOrder} \times \frac{1000}{10^6} \quad (4)$$

The results obtained are shown in Fig. 5 (UL) and Fig. 6 (DL) for end devices, and in Fig. 7 for sensors (only UL has been considered for sensors). The results presented are for an MCS value of 28. These figures compare the capacity needed by end devices and sensors to transmit in 1ms the traffic pattern chosen in Table 2 versus the actual capacity that 5G can support depending on different configurations (Table 4). As can be seen in Fig. 5 and Fig. 6, the maximum capacity supported by DL is higher than the maximum capacity supported by UL. This is due to the fact that UL needs more resources to transmit control signals than DL (Table 3). Apart from that, an MCS 28 configuration is able to handle correctly all the traffic required by 30 sensors (Fig. 7), while in the case of end devices, for UL (Fig. 5), 5G with FR1 and 1 antenna is not able to transmit the chosen data having 25 or more nodes.

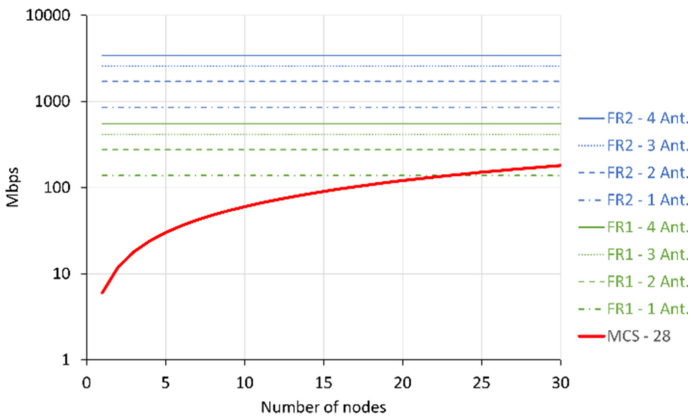


Fig. 5. Required traffic vs 5G capacity (UL) – MCS 28 (end devices) (Color figure online)

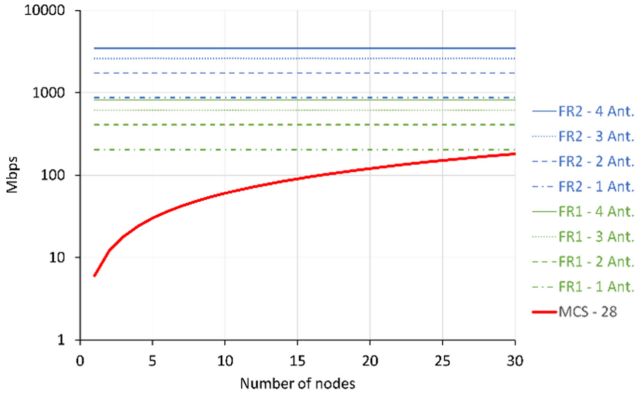


Fig. 6. Required traffic vs 5G capacity (DL) – MCS 28 (end devices) (Color figure online)

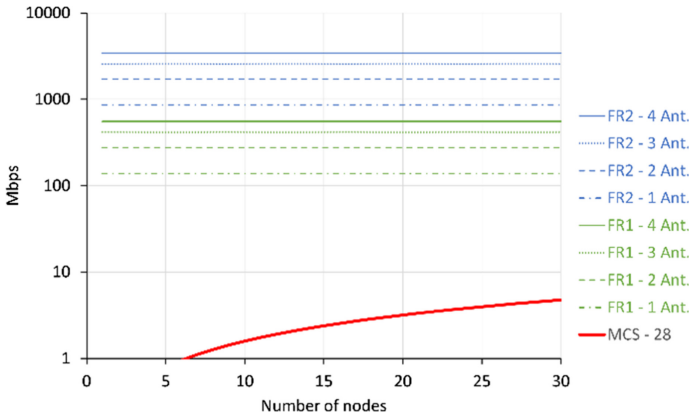


Fig. 7. Required traffic vs 5G capacity (UL) – MCS 28 (sensors) (Color figure online)

In order to plot the maximum network size in each configuration, the crossing of the traffic requirement (red plot) is done with the green/blue lines (Fig. 5, Fig. 6 and Fig. 7) indicating the 5G capabilities for MCS 0, 10, 20 and 28. The results are plotted in Fig. 8 (a) (UL, end devices), Fig. 8(b) (DL, end devices) and Fig. 9 (UL, sensors). As already known, with lower modulation, a higher bit rate is needed to transmit the same amount of data within the same period, in our case within 1ms, than with a higher modulation. Therefore, in the case of end devices (Fig. 8), 5G is not able to transmit the required data (Table 2) with any single node having a configuration of MCS 0. As the MCS is increased, the number of nodes that can transmit at the same time increases, in the case of DL up to 30 nodes can transmit using a MCS of 28 in both FR1 and FR2 (Fig. 8(b)). In the case of sensors (Fig. 9), both FR1 and FR2 are able to cover the whole network of 30 nodes using either MCS 10, 20 or MCS 28.

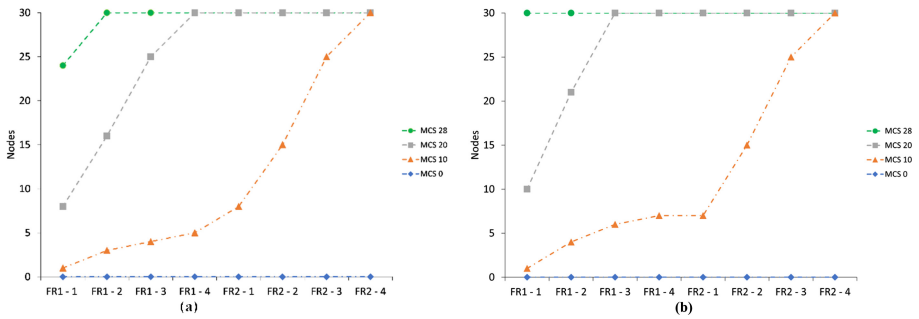


Fig. 8. Maximum network size (a) UL and (b) DL – end devices

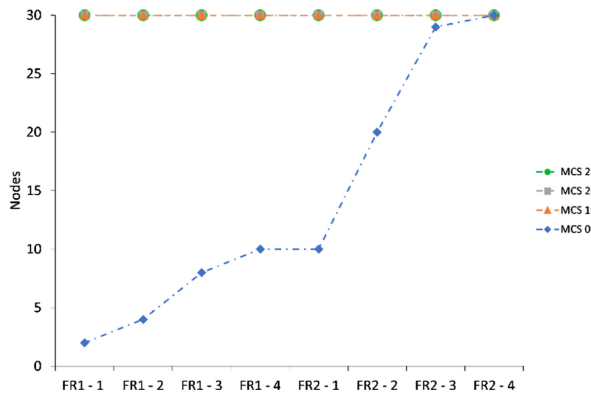


Fig. 9. Maximum network size UL – sensors

7 Conclusions

In this paper an analysis has been done about the usage of 5G technology as a replacement for the current wired network inside train consists. For this purpose, the required traffic values have been obtained both for end devices and sensors, and this traffic has been mapped against the capabilities offered by different configurations of 5G. Obtained results indicate that 5G is a potential technology for sensor and end devices communication in the WLCN, even though specific MCS configurations should be selected for maximum node coverage in worst-case traffic scenarios.

Finally, it should be noted that the analysis presented in this paper has been focused on TCMS traffic, but train devices also generate On-Board and Multimedia Services (OMTS) traffic, which includes streaming audio, video and best effort data. This traffic has more relaxed time requirements than TCMS, and therefore could be covered by a separate wireless system with different capabilities.

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