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Meriem Mhedhbi, Mira Morcos, Ana Galindo-Serrano, Salah Elayoubi. Performance Evaluation of 5G Radio Configurations for Industry 4.0. WiMob 2019 - 15th International Conference on Wireless and Mobile Computing, Networking and Communications, Oct 2019, Barcelone, Spain. 10.1109/wimob.2019.8923609 . hal-03687385

HAL Id: hal-03687385

<https://inria.hal.science/hal-03687385>

Submitted on 3 Jun 2022

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Performance Evaluation of 5G Radio Configurations for Industry 4.0

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Abstract—The future Radio Access Network (RAN) is being engineered to accommodate the emergence of Ultra Reliable Low Latency Communications (URLLC) and to handle the possible coexistence between URLLC and enhanced Mobile Broad Band (eMBB) services. To achieve this, new features are being implemented in the future RAN to fulfill the strict requirements of the URLLC traffic in terms of latency and reliability. In this paper, we exploit the radio frame features in the New Radio (NR) and evaluate the users' performances in Downlink (DL) scheme. We conduct extensive system level simulations in realistic network deployment considering the Industry 4.0 use case. We study the impact of 1) different radio configurations and 2) the dedication of a reserved bandwidth to the critical traffic, on the URLLC achieved user plane latency and packet loss probability. The coexistence of URLLC and eMBB traffic is also evaluated by measuring the eMBB users' throughput.

Keywords: Fifth-Generation (5G), URLLC, Industry 4.0, System level simulations.

I. INTRODUCTION

The Fifth-Generation (5G) of mobile network [1] is designed to handle the traffic of diverse devices with heterogeneous requirements in terms of Quality of Service (QoS). In particular, the accommodation of mission critical services on top of enhanced Mobile Broad Band (eMBB) services imposes additional constraints on the design of the Ultra Reliable Low Latency Communications (URLLC) services that are extremely demanding in terms of latency and reliability.

Among the URLLC services, industry automation is a key component to smart manufacturing. This use case has been identified in the 3rd Generation Partnership Project (3GPP) and requires an end-to-end latency lower than 1 ms and a Block Error Rate (BLER) target of 10^{-5} [2]. The shift to wireless technologies will help factories increase the production efficiency and also reduce the costs, compared to traditional cabled setups, and by that ease the automation process [3], [4].

Several studies proved that the latency required by URLLC systems could be achieved by optimizing both the core and radio networks [5]. In particular, at the radio level, as the main contributors to latency are the Physical (PHY) and Medium Access Control (MAC) layers [6], multiple solutions are being proposed to reduce the latency induced at these levels and help achieve the very low latency and high reliability required by URLLC. To mention some of these features we find mini-slot, DL preemption, flexibility in numerology and also the

flexible usage of Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD).

The studies in [7], [8] show that shortening both Transmission Time Interval (TTI) and the required time for retransmitting the packet, is suitable to achieve hard URLLC latency requirements. The impact of the DL preemption technique on the user plane latency and its coexistence with eMBB are evaluated in [9], [10]. The authors in [11] focus on optimizing the Hybrid Automatic Repeat Request schemes (HARQ) to achieve a target latency. It has been shown that the saved time for the Grant Request (GR) could be useful for more HARQ retransmissions and thus enhancing both transmission latency and reliability [12].

In addition to the above-mentioned general scope URLLC works, few papers discussed the factory automation use case. In [13], a joint resource allocation and Modulation Coding Scheme (MCS) was analyzed while considering reliability and latency constraints. The authors in [14] evaluated the performance at system level for the industrial scenario by considering different waveforms for mixed numerologies. The results show that with the adequate 5G radio configuration, the required low-latency and high reliability for industrial applications can be achieved. Network slicing is presented in [15] to handle the various types of industrial communications and their heterogeneous requirements in terms of reliability and latency.

In this paper, we conduct and analyze system level simulations for the industry automation use case. We specifically evaluate the DL user plane latency achieved by exploiting different radio configurations at the PHY and MAC layers. We build on the system level simulator described in [16] and focus on the industry automation use case by considering an optimized and more realistic network configuration.

The contributions of this paper are articulated as follows:

- We quantify the achievable latency for the industrial network scenario, based on realistic and complete system level simulations.
- We identify NR configurations that are more suitable for Industry 4.0 applications.
- We investigate the impact of dedicating a reserved bandwidth to URLLC services.
- We study the coexistence of the URLLC and eMBB traffic and evaluate the impact of the dedicated bandwidth on the eMBB users' throughput.

This paper is organized as follows: Section II introduces the system model we based our study on. Section III describes the scenario we evaluated and discusses the results obtained from simulations: achievable latency and packet loss probability for URLLC users' and eMBB users' throughput. Finally Section IV draws useful conclusions and recommendations for designing URLLC systems.

II. SYSTEM MODEL

In this section, we emphasize on the different NR features related to URLLC traffic implemented in our system level simulator. We also present the delay model used to estimate the user plane latency and describe the resource allocation scheme we adopted to schedule URLLC and eMBB users.

A. NR Configurations

As Long Term Evolution (LTE), NR adopts the Orthogonal Frequency Division Multiplexing (OFDM) scheme. Each TTI occupies N_{OFDM} symbols and the transmission bandwidth B is divided into N_{RB} Resource Blocks (RBs). The number of Resource Elements (REs) per RB is $N_{RE} = 12$. However, unlike LTE legacy where, $N_{OFDM} = 14$ symbols and the Sub-carrier spacing (SCS) $\Delta f = 15$ kHz, NR offers more flexible features to satisfy the URLLC users' requirements in terms of latency. NR enables:

- **Flexible numerology:** where different SCSs are adopted to satisfy the latency requirements of URLLC. These SCSs are obtained from scaling up the LTE-base SCS $\Delta f = 15$ kHz by 2^μ , where $(\mu = 1, 2, \dots)$. The TTI duration is scaled down by 2^μ , enabling faster transmission and lower processing time [17]. Table I presents the supported SCS and the associated TTI duration.
- **Mini-slots:** where N_{OFDM} can be of 2, 4 or 7, enabling more flexible and faster scheduling opportunities.

In addition to the different numerologies, NR allows different radio configurations for the 5G frequency bands. Several frequency bands will be used by operators all around the world: low range bands called FR1 which comprehend both FDD and TDD bands and high range bands called FR2 composed of centimeter and millimeter waves bands, using TDD. We will call the association of a frequency band, a numerology and a duplexing mode a "NR configuration". The configurations supported in the standard are presented in Table I. Note that results in Section III consider only 8 possible configurations.

Table I: NR configurations

Frequency	SCS (kHz)				BW (MHz)	Duplex
	15	30	60	120		
	TTI Duration (ms)					
	1	0.5	0.25	0.125		
700 MHz	✓	✓	-	-	[10, 20]	FDD
3.5 GHz	✓	✓	✓	-	[10, 100]	TDD
26 GHz	-	-	✓	✓	[50, 400]	TDD

The main objective of this paper is to assess the suitability of these configurations for industry automation scenarios.

B. Traffic model and resource allocation

The URLLC traffic is modeled as short size packets of L information bits, arriving to the gNodeB (gNB) buffer according to a periodic deterministic traffic model as advocated by the Release 16 of the NR specifications [18] for the industry 4.0 use case. URLLC users share resources with eMBB users which we consider to have a full buffer type of traffic. This means that eMBB users have unlimited packets to transmit.

In order to satisfy requirements of both traffic types, we adopt a scheduling algorithm that can perform bandwidth sharing while satisfying the stringent requirements of URLLC users in terms of latency and also guaranteeing a minimum quality of service for eMBB traffic. This is achieved by according a priority to the URLLC traffic by scheduling the URLLC users first with a minimum bandwidth reservation for eMBB users. The scheduling algorithm runs as follows:

- A fraction of the bandwidth, that is equal to αB , is allocated to URLLC users in a cyclic way with respect to their packets arrival time in the gNB buffer.
- The same allocation policy is applied to eMBB users in the rest of bandwidth equal to $(1 - \alpha)B$, at minimum, i.e., RBs in αB not allocated to URLLC users, can be allocated to eMBB users.

Figure 1 illustrates the bandwidth sharing strategy we implement in our system level simulator.

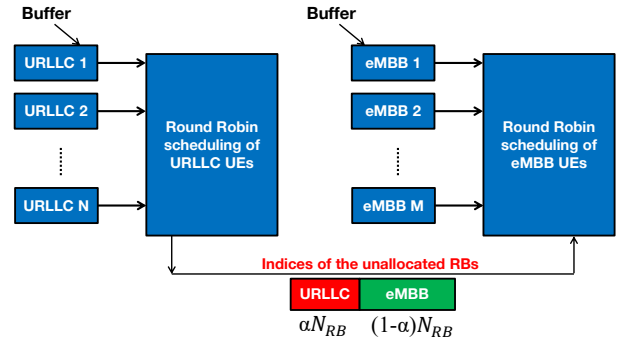


Figure 1: Scheduling strategy of URLLC and eMBB traffic

The resource allocation is performed as follows:

- The scheduler manages a queue where generated packets are stored until they are correctly delivered.
- At each time slot, the scheduler checks if there are URLLC packets awaiting service in the buffer. If so, they are allocated resources starting from the oldest packet until all URLLC packets are served or the maximum reserved resources αB is attained. eMBB packets are then served on the remaining resources following a round robin discipline.
- When serving a packet, the number of required RBs is determined for each MCS satisfying the target BLER, according to the modulation order, the coding rate, the RB size and the packet size. If several MCS satisfy these conditions, we select the MCS that offers the best spectral efficiency.

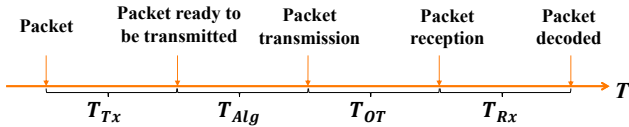


Figure 2: Delay model for one transmission

- In case of no MCS achieving the target BLER requirement with the available RBs, which means the channel quality is bad or the amount of available RBs is low, the packet is delayed until the channel quality becomes better or more resources are available in an upcoming TTI.

Note that, for implementing this scheduling scheme in our system level simulator, we use lookup tables providing for each MCS the BLER versus Signal to Interference Noise Ratio (SINR) in an Additive White Gaussian Noise (AWGN) Channel. These link level curves are obtained using link level simulations and are able to feed system level simulator. Classical 4G-like turbo coding is implemented for eMBB, while enhanced turbo coding is used for URLLC for allowing very low BLER [19].

C. Latency model

When evaluating the delay, we focus particularly on the PHY and MAC layers user plane latency which is the contribution of the radio network to the time from when the source sends a packet to when the destination receives and decodes it correctly. It is defined as the one way duration it takes to successfully deliver an application layer packet, assuming the mobile station is in the active state.

Let us denote by Δ_{UE} and Δ_{gNB} , the processing delays by the gNB and User Equipment (UE), respectively, for transmitting and processing a packet. At UE side the processing delay is given in terms of OFDM symbols and depends on the SCS. Table II gives the processing delays for UE category 1 [20], used in our simulations. The 3GPP standard plans to include a second category of advanced UEs with shorter processing delays in Release 16. Regarding the gNB side the processing delay is assumed to be 1 TTI.

Table II: 5G NR processing delays

SCS(kHz)	15	30	60	120
Δ_{UE} (OFDM symbols)	8	10	17	20
Δ_{gNB} (TTI)	1			

Figure 2 depicts the delay model and presents the four component of one way user plane latency T_{radio} which is given by the following equation:

$$T_{radio} = T_{Tx} + T_{Alg} + T_{OT} + T_{Rx} \quad (1)$$

where, T_{Tx} represents the transmitter processing time which in our case is equal to Δ_{gNB} . T_{Alg} is the frame alignment delay and represents the required time a packet, ready to be

transmitted, should wait until the transmission can start. T_{OT} corresponds to the over air transmission time and is exactly the TTI duration. Finally T_{Rx} is the receiver processing time and corresponds here to Δ_{UE} . In case of HARQ retransmission and additional T_{HARQ} delay should be included.

III. SIMULATION RESULTS

In this section, we start by describing the simulation setup and the radio frame configurations we aim to evaluate. Then, we present the simulation results in terms of URLLC users' latency and packet loss probability and eMBB users' throughput.

A. Simulated scenario: Industry 4.0

We consider the scenario of a typical factory including a set of wirelessly connected robots. Each robot is equipped with an URLLC transceiver that communicates with a central controller via a set of gNBs deployed within the factory. For simulation purposes we consider, as presented in Figure 3, a service area of $160\text{ m} \times 160\text{ m}$ and 280 robots distributed in 5 production lines, as given in 3GPP scenario [21]. In addition, 5 eMBB users are randomly located within the service area in order to measure the impact of URLLC traffic over the eMBB ones.

We consider the deployment of 2 tri-sector gNBs with 2 antennas per sector placed on the ceiling at 10 m high. We adopt the pathloss and shadowing models of the 3GPP indoor office, presented in [22]. We also take into account the blockage effect induced by the movement of metallic obstacles between robots' transceivers and the gNBs. This effect is introduced by metallic blockers that change their position at every TTI.

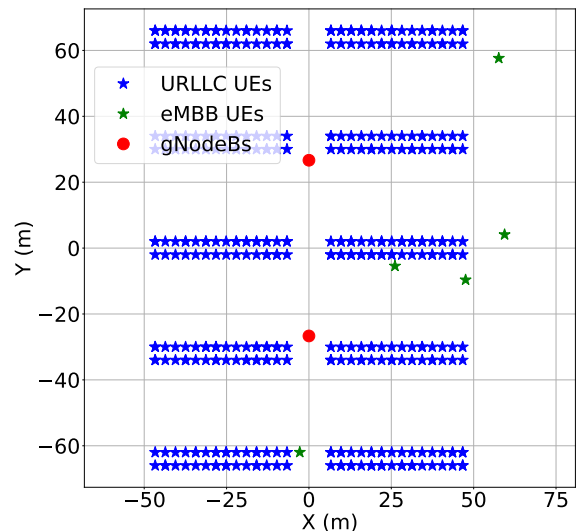


Figure 3: Simulated Industry 4.0 scenario

In our scenario, we consider periodic traffic model for URLLC users with 1 ms periodicity between consecutive

Table III: Simulated configurations

Configuration number	1	2	3	4	5	6	7	8	9
Carrier frequency (GHz)	0.7				3.5			26	
Bandwidth (MHz)	10				50			100	
Duplex mode	FDD				TDD				
Frame configuration	-				DDDSU			DU	
Sub-carrier spacing (kHz)	30				60			120	
Mini-slots	2	4	2	4	2	4	7	7	7
Number of URLLC users	280		20		280				

packets. The URLLC users packet size, L , is 96 bits and the BLER target 10^{-5} . Please notice that in our simulations the URLLC traffic has a full priority with $\alpha = 1$, which means that no eMBB packet can be transmitted unless all URLLC packets in the buffer are scheduled. Regarding the eMBB traffic, we consider full buffer where the packet size depends on the number of users and available RBs. The target BLER for eMBB is 10^{-1} .

The NR configurations, given in Table III, are evaluated through system level simulations in order to compare their performances in DL scheme in terms of latency, packet loss and throughput. While the 3GPP traffic scenario of 280 robots is simulated for all frequency bands, a low traffic scenario is also considered for the 700 MHz band as it is a resource-limited band.

B. Performance evaluation

1) *Latency results:* The set of results given by Figures 4, 5 and 6, present the percentage of successfully URLLC decoded packets as a function of the user plane latency for the evaluated configurations. The latency axis is divided into sub-intervals, where we present the percentage of correctly received packets in each sub-interval.

Figure 4, top, presents the results achieved at 700 MHz corresponding to configurations 1 and 2 in Table III, considering 280 URLLC users. We notice that the percentage of decoded packets at short delays, i.e., below 1 ms, is lower than 10% per sub-interval. Besides, the decaying behaviour of the latency distribution above 1 ms, suggests a channel congestion i.e., at each TTI a very limited number of packets, compared to the total number of generated packets, is transmitted.

Based on these observations, we reduced the number of URLLC users to 20, where we considered 2 robots per production line. The results are presented in Figure 4, bottom, for configurations 3 and 4 presented in Table III. We can observe that the user plane latency distribution presents a completely different behavior and 100% of the received packets delay is always below 1 ms, for both 2 and 4 OFDM symbols per mini-slot. Please notice that, at this frequency, the bandwidth is 10 MHz and the available number of RBs is limited. Thus, the FDD 700 MHz band can guarantee low latency but only for a limited number of UEs.

At 3.5 GHz, we face a different behavior in the latency distribution due to the TDD frame structure, which highly impacts the transmission delays, which highly impacts the transmission delays. We assume the frame configuration at 3.5 GHz band to be “DDDSU”, i.e., three downlink sub-frames, one special uplink sub-frame and one uplink sub-frame.

In fact, the frame structure has a direct impact on the alignment delay which varies, in this case, from 0 to 3 TTIs. Thus, the distribution spread out is explained by the waiting time for the next DL sub-frame.

Regarding the latency, in case of a stringent latency requirements, we can resort to configurations 5 and 6 to decrease the transmission delays, reaching almost 1 ms. The latency achieved at 3.5 GHz shows that configuration 7 is suitable for use cases with less stringent latency requirement, since the delay goes up to 1.5 ms.

Regarding the channel capacity, configurations 5, 6 and 7 are able to handle the 280 robots. The choice of the configuration at 3.5 GHz will be then related to the latency requirement, i.e., configuration 7 is suitable only for a slightly relaxed latency constraint and if the 1 ms constraint is strict, configurations 5 and 6 are recommended.

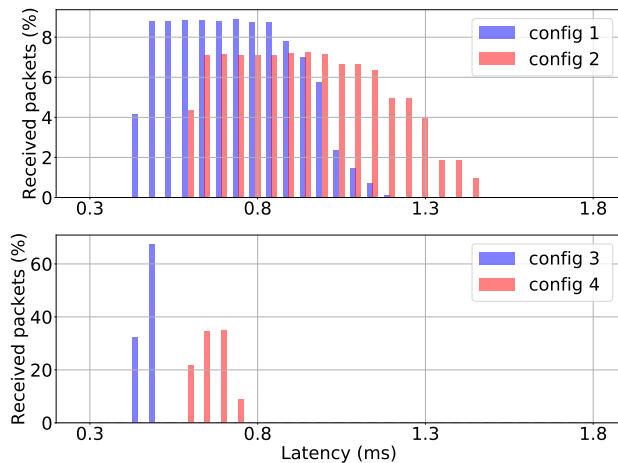


Figure 4: Latency results at FDD 700 MHz: top for configurations 1 and 2 and bottom for configurations 3 and 4

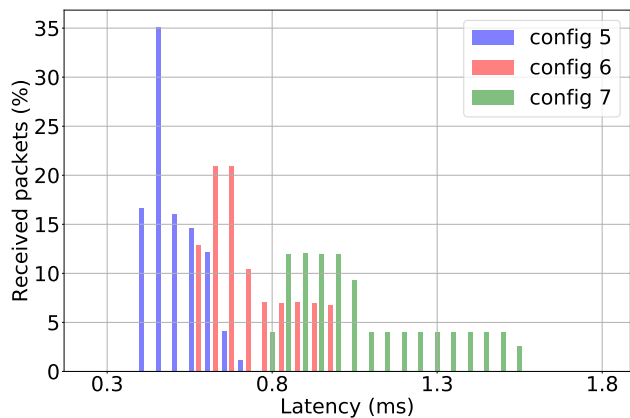


Figure 5: Latency results at TDD 3.5 GHz for configurations 5, 6 and 7

In order to achieve both capacity and latency objectives, the millimeter waves appears to be an interesting option. They offers larger bandwidth (from 100 MHz up to 200 MHz) and higher SCSs (60 and 120 kHz) which means shorter TTIs. Figure 6 presents the latency results for configurations 8 and 9 in Table III and shows that for both cases, 100% of the packets delays are less than 1 ms. Furthermore configuration 9 is able to achieve a delay lower than 0.5 ms.

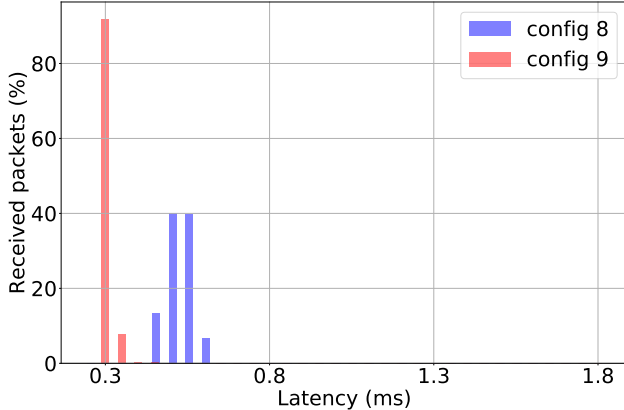


Figure 6: Latency results at TDD 26 GHz for configuration 8 and 9

2) *Packet loss results:* The packet loss probability is one of the crucial criterion to take into account in URLLC use cases. In this study, in order to estimate it, we consider three types of packet loss possibilities:

- **Retransmission drop:** occurring when the number of retransmission of a given packet exceeds a fixed threshold. In our simulations, for URLLC traffic, we set the retransmission threshold to 3.
- **Latency drop:** occurring when a packet transmission delay is higher than the predefined latency budget. The presented results are estimated for latency budget of 1 ms.
- **Buffer drop:** occurring when the waiting time of a given packet in the buffer exceeds the latency budget.

Thus, we define the packet loss probability as the ratio between generated packets and dropped packets.

Figure 7 presents the packet loss probability for the different simulated configurations. It exhibits the average packet loss probability over the URLLC users and the maximum users' packet loss.

The results show a high packet loss probability average around 0.1 and 0.5 for configurations 1 and 2, respectively, which is due to the latency drop, as the delay distributions in Figure 4 show. The problem originates from the limited number of RBs, leading to a high waiting time for the packets to be scheduled and transmitted. The packet loss probability is more reasonable for configuration 3 and 4 being of 4×10^{-5} and 1.4×10^{-4} , respectively. For configurations 1 and 3 mini-slot is of 2 OFDM symbols and all the packets are lost due to latency drop. However when using mini-slot of 4 OFDM symbols, which is the case of configurations 2 and 4, some packets are

also dropped in the buffer. In this case, the TTI duration is longer and thus the waiting time of a packet to be transmitted is longer. The packet loss probability results at 3.5 GHz are similar to 700 MHz, where the packets are lost due to the stringent latency budget. By increasing the number of OFDM symbols per time slot, we lengthen the TTI duration. Thus, the transmission delay increases and the number of packets lost due the strict latency budget increases too. The average packet loss probability is $2.8 \cdot 10^{-4}$, 0.006 and 0.6 for configuration 5, 6 and 7 respectively.

For configuration 8 the packet loss probability is 4×10^{-4} and decreases to be quasi null, when we increase the SCS to 120 kHz, i.e configuration 9, where we dispose of enough resources and very short TTI duration. So, all generated packets are transmitted and correctly received within the latency budget.

3) *Throughput results:* The main objective of this study is to evaluate the performance relative to URLLC users in terms of the latency and reliability. In our simulations, URLLC traffic is given the highest priority, by fixing $\alpha = 1$. However, it is of paramount importance of ensuring an eMBB traffic. To do this we introduced 5 eMBB users, with full buffer traffic model.

Figure 8 represents the average throughput of eMBB users for configurations 5 to 9. Please notice that results at 700 MHz are not presented, because we do not have enough resources to serve both URLLC and eMBB traffic. For the rest of configurations, results show that the average throughput can vary from 40 to 75 Mbits/s and thus, the eMBB traffic can be handled with a satisfying quality of service. Figure 8 presents also, in red line, the standard deviation of eMBB users throughput. It shows that the throughput can reach 75 Mbits/s for configurations 5, 6 and 7 and 140 Mbits/s for configuration 8 and 9.

IV. CONCLUSION

In this paper we considered the Industry 4.0 use case and evaluated the performance of different radio configurations in terms of latency, packet loss probability and throughput.

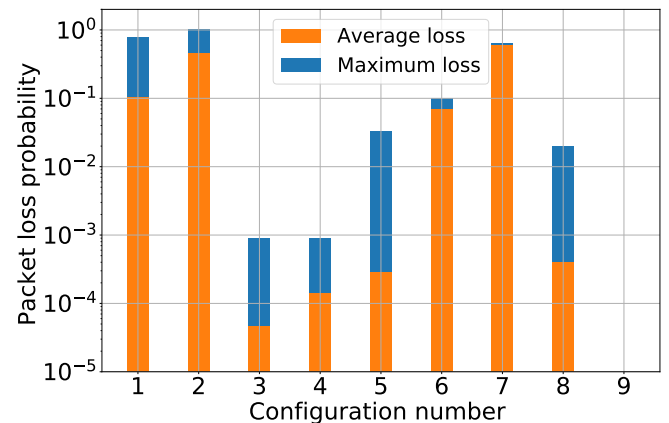


Figure 7: Packet loss probability

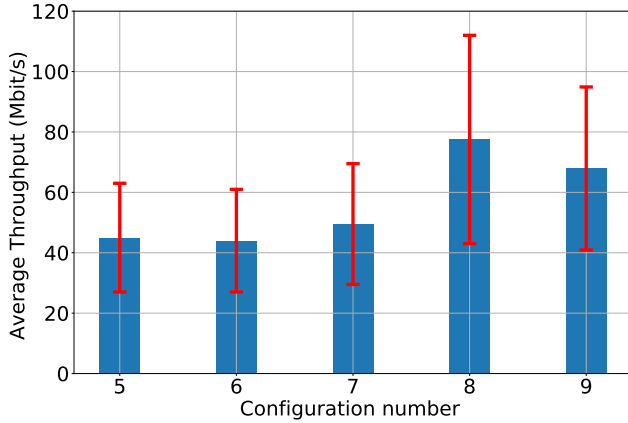


Figure 8: eMBB users throughput results

Regarding the latency, we studied in particular the user plane latency taking into account the radio, processing and buffer delays. We illustrated the distribution of the latency for different configurations and showed that the deployments at 700 MHz can offer short delays suitable for the industry 4.0 scenario, but only for a limited number of users. At 3.5 GHz, dense scenario is supported but only for use cases more relaxed in terms of latency because of the TDD duplex mode and the frame configuration. Only 2 OFDM symbols per mini-slot configuration could be the solution for strict latency scenarios. Finally, configurations at 26 GHz present the best delay results even for 280 robots. The packet loss probability results are congruent with the latency distribution, since the packets are lost mainly due to the latency budget. The same conclusion holds with eMBB users throughput, where the eMBB traffic is absent at 700 MHz. For the rest of configurations, we showed that we can guarantee a high quality of service for the eMBB traffic.

As for future perspectives, we aim to study further use cases in Wide Area Network (WAN) environment and also to implement and to evaluate advanced scheduling techniques for better eMBB and URLLC traffic coexistence.

ACKNOWLEDGEMENT

This work has been performed in the framework of the H2020 project 5G-SMART co-funded by the EU. The authors would like to acknowledge the contributions of their colleagues. This information reflects the consortium's view, but the consortium is not liable for any use that may be made of any of the information contained therein.

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