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5G NR Configured Grant in ns-3 Network Simulator for Ultra-Reliable Low Latency Communications

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Abstract

5th Generation (5G) and Beyond networks are being designed to support Ultra-Reliable and Low Latency Communications (URLLC). To this end, 5G defines a new radio (NR) interface with a new mechanism at the Physical (PHY) and Medium Access Control (MAC) layers that allow reducing the latency communication. One key mechanism to reduce the latency is the scheduling scheme. Mainly, 5G defines the use of the configured grant (CG) scheduling for uplink (UL) transmissions that eliminates the need to request and assign resources for each packet transmission by pre-allocating resources to the UE. The availability of simulation tools that accurately model the new mechanisms and technologies incorporated in 5G New Radio (NR) is key to research and evaluate new proposals and enhancements to meet the communication requirements of emerging services. In this context, this paper presents the implementation of the configured grant scheduling in the ns-3 network simulator. Remarkably, the configured grant has been implemented within the 5G-LTE-EPC Network simulAtor (5G-LENA) module that simulates the fundamental PHY-MAC NR features in line with the NR specifications. In addition, this paper validates the configured grant implementation through system-level simulations considering a typical Industry 4.0 scenario characterized by applications demanding URLLC.

Keywords: Configured Grant, 5G, NR, semi-static scheduling, URLLC, ns-3, 5G-LENA, software simulation

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1. Introduction

5G and Beyond networks are being designed to efficiently support very different applications and services with diverse and stringent communication requirements not only in terms of bandwidth and transmission rates but also in terms of reliability and latency. The support of URLLC is key in verticals with increasing levels of automation, such as manufacturing or transportation. 5G incorporates an NR interface that defines new mechanisms and technologies to reduce the contribution of the PHY and MAC mechanisms to the communication latency [1]. At the PHY layer, 5G NR defines a more flexible frame structure, the use of flexible numerology that allows using transmission slots with shorter time-domain (between 1 and 0.0625 ms), and the possibility to use minislots [2]. At the MAC layer, one of the mechanisms that significantly contributes to the communication latency is the scheduling scheme. To reduce this delay, 5G NR introduces semi-static scheduling schemes [3] (referred to as grant-free scheduling), in addition to the dynamic scheduling, that pre-allocate resources to UEs and eliminate the need to request and allocate resources before transmitting each packet.

The availability of simulation tools that accurately model the new mechanisms and technologies incorporated in 5G NR is key to researching and evaluating new proposals and enhancements to meet the communication requirements of emerging services. In this context, it is possible to find in the literature different simulation tools developed to this end. For example, [4] and [5] have developed the necessary software tools to evaluate the basic connectivity of devices to a 5G network. However, these tools are not open to the research community. Open simulation tools are very interesting options since it aggregates the efforts of the research community to develop powerful and accurate simulation environments. OMNeT++ and ns-3 discrete event network simulators are two powerful open-source network simulators that implement modules for the simulation of the 5G NR. In the case of OMNeT++, Simu5G [6] models the different features of 5G NR such as carrier aggregation, different numerologies, and frequency/time division duplexing. On the other hand, ns-3 incorporates a pluggable 5G-LTE-EPC Network Simulator (5G-LENA) module [7] to simulate 5G networks. 5G-LENA implements the 5G NR features at the PHY and MAC layers, such as configurations of the NR frame structures through different numerologies, operations through multiple Bandwidth Parts (BWP), or dynamic scheduling for UL and DL transmissions. Both simulators are very powerful and offer significant advantages for studying and evaluating 5G networks. However, to the best of the authors' knowledge, neither of them implements configured grant, a key mechanism for studying URLLC communications.

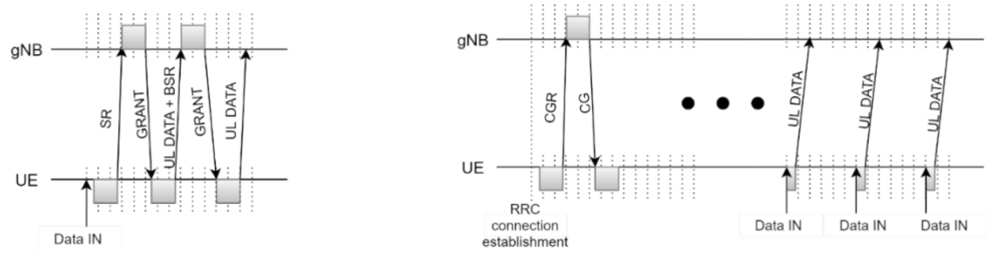
We have considered using the 5G-LENA simulator as a tool to support and evaluate our research about the implementation of 5G and Beyond networks to support the communication requirements of critical Industry 4.0 applications. We selected 5G-LENA because it was the unique 5G NR simulator available when starting this study (Simu5G was released after 5G-LENA). To this end, it is necessary to implement the semi-static scheduling in the simulation tool essential to support URLLC applications. In this context, this paper presents the implementation of the semi-static scheduling defined in 5G NR [8] for uplink transmissions (this is referred to as configured grant). We focus on the UL since it is the link where the semi-static scheduling potentially provides higher latency reductions compared with the use of dynamic scheduling; in the uplink, the user equipment (UE) has to request resources to the new generation Node B (gNB) and wait for the allocated resources before transmitting a packet. In addition, we validate this implementation through system-level simulations and compare the performance results with analytical values available in the literature. In addition, we present initial evaluations to show the potential of this software tool to evaluate the potential of configured grant to support Industry 4.0 applications with stringent latency requirements.

The rest of the paper is structured as follows. Section 2 describes the different mechanisms included in 5G NR for radio resource allocation. Section 3 presents the 5G-LENA module. Section 4 presents the implementation of the configured grant scheduling in 5G-LENA module. Section 5 validates the implemented code. Section 6 outlines the main conclusions.

2. Radio resource allocation in 5G New Radio

5G-NR introduces dynamic and semi-static scheduling for supporting services with different communication requirements and traffic patterns [8]. With dynamic scheduling, radio resources are dynamically allocated by the gNB for each packet transmission in downlink (DL) and UL. For each packet to be transmitted in the DL, the gNB informs the corresponding UE about the allocated radio resources where the packet will be transmitted. The control message with the scheduling information is transmitted. When a UE wants to transmit a packet in the UL using dynamic scheduling, the UE sends a scheduling request (SR) to the gNB. After the scheduling decision, the gNB sends a grant message to the UE that contains the information about the allocated resources. Then, the UE can transmit the packet using the allocated resources. If the UE was not able to transmit all the data in the allocated resources, the UE sends the Buffer Status Report (BSR) together with the data packet to inform the gNB about the amount of data pending to be transmitted. Based on this information, the gNB takes a scheduling decision and sends a grant with the information about the allocated resources to the UE. When the UE receives the grant, it can transmit a new data packet in the allocated resources. This process continues as long as the UE has data to transmit. Fig. 1.a illustrates the dynamic scheduling process for UL transmissions.

The signalling exchange between the UE and the gNB to request/inform about the allocated resources results in a non-negligible delay that can compromise the feasibility of services demanding low latencies, and this latency is more relevant in the UL where two messages need to be exchanged. For example, this signalling exchange results in latency values for UL transmissions between the UE and the gNB in 5G NR of 4.5 and 2.5 ms when using 15 kHz subcarrier spacing and a 14 and 7 symbols-slot respectively [9]. It is important to highlight that these values do not meet the 1 ms-latency requirement established by the 3rd Generation Partnership Project (3GPP) Release 16 in [10] as a general latency requirement for URLLC services[1]. To reduce this latency, 5G NR introduces the use of semi-static scheduling, referred to as semipersistent scheduling (SPS), and configured grant (CG) for DL and UL transmissions, respectively [8]. With SPS and CG, radio resources are pre-assigned periodically to the UEs. In this context, when a packet is generated, it can be transmitted immediately in the pre-allocated resources. SPS and CG eliminate the need to exchange signaling messages to request/grant resources for each packet and therefore reduce the transmission latency. With SPS, the periodicity of the pre-allocated DL resources is configured by Radio Resource Control (RRC) signalling when the connection is established, and the allocated DL resources can either be signalled, activated, or deactivated by control messages [8]. In the UL, the 3GPP defines two types of CG: Type 1 and Type 2. With Type 1, the configured uplink grant, including the periodicity, is configured by RRC signaling at the connection establishment. CG Type 2 is similar to SPS. With CG Type 2, the periodicity of the configured UL grant is defined by RRC signaling at the session establishment, while the configured UL grant is either signalled, activated, or deactivated by control messages [8]. Fig. 1.b illustrates the CG scheduling (Type 1) for UL data transmissions.



a) Dynamic scheduling b) CG scheduling

Fig. 1. Signal flow for UL transmissions (shadow rectangles represent the processing times at the gNB and the UE).

3. 5G-LENA Network Simulator

5G-LENA is an open-source discrete-event network simulator of the 5G NR ([11], [7]). It is implemented over ns-3 [12]. ns-3 is an open C++ simulation environment for networking research. The ns-3 simulator offers a solid simulation core that supports research on both IP and non-IP-based networks. LENA [7] was initially developed to implement the Radio Access Network (RAN) and the core network of Long Term Evolution (LTE). 5G-LENA is the evolution of LENA for the simulation of 5G NR. This evolution focused first on the RAN. The 5G-LENA module implements the fundamental PHY-MAC NR features in line with the NR specifications [8].

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[1] 3GPP Release 16 establishes in [10] as a general requirement for URLLC services that a packet of 32 bytes must be transmitted with a reliability of $1\text{-}10^{-5}$ and a latency deadline of 1 ms.

The 5G NR RAN is modeled in the RAN C++ class. The RAN class implements two different C++ classes to simulate the functionalities of the gNB (NrGnb class) and the UE (NrUe class). In addition to the PHY and MAC layers, where the main NR features are implemented, the upper layers, Radio Link Control (RLC), Packet Data Convergence Protocol (PDCP), and RRC of the protocol stack are implemented for the gNB and the UE. The RLC, PDCP, and RRC layers currently rely on LTE LENA implementation. The C++ classes that implement the MAC and PHY layers for the gNB are the NrGnbMac and NrGnbPhy classes, and for the UE are the NrUeMac and NrUePhy classes. The NrGnbMac and NrUeMac classes contain the NrMacSchedulerNs3 class that implements the scheduler for the UL and DL transmissions. The NrMacSchedulerNs3 class uses the functions implemented in the NrMacSchedulerOfdma and NrMacSchedulerTdma classes to allocate resources based on Orthogonal Frequency Division Multiplexing Access (OFDMA) or Time Division Multiplexing Access (TDMA). The NrGnbPhy and NrUePhy classes implement the different numerologies defined in 5G NR (numerologies 0 to 4 with subcarrier spacing equal to 15, 30, 60, 120, and 240 kHz, respectively) [2], and properly model the numerology-dependent slot and OFDM symbol granularity (see [4]). Therefore, the PHY layer of the 5G LENA is able to support the flexible NR frame structure in the time domain and model the transmission and reception of data and control channels through the NrSpectrumPhy class that models the radio channel.

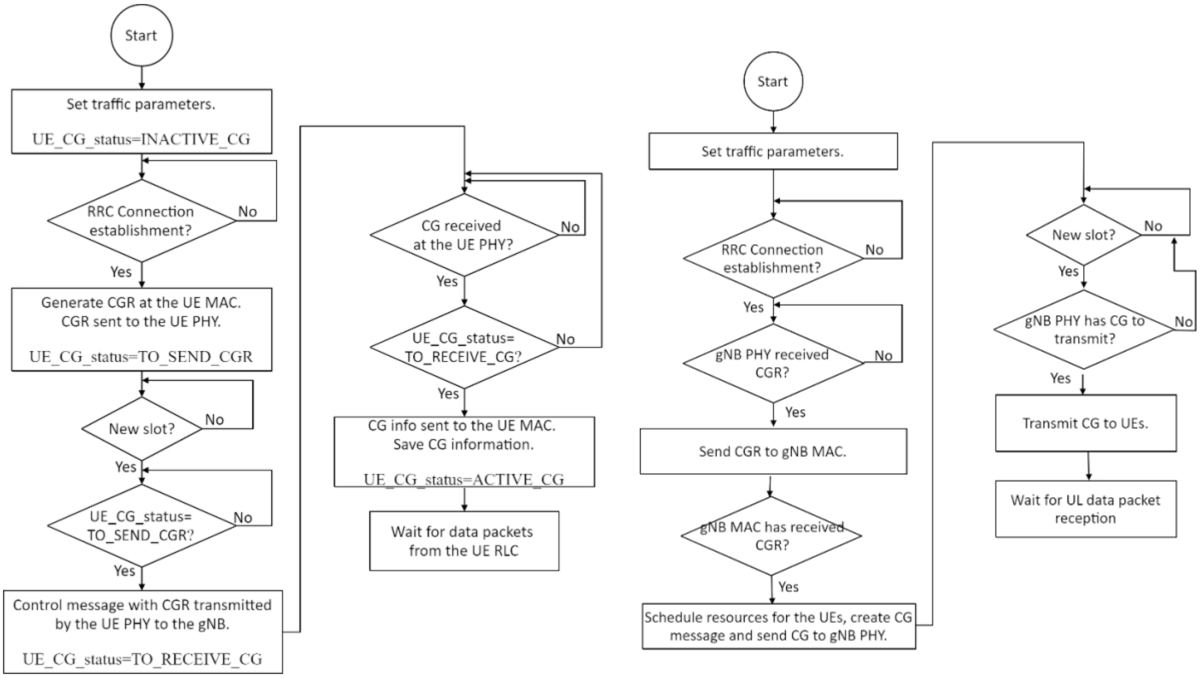
5G-LENA only implements dynamic scheduling for UL and DL transmissions [7]. When a new data packet generated in the UE arrives to the MAC layer from the upper layers, the UE needs to send an SR to the gNB to request radio resources for the transmission of the packet (as presented in Section 0). In this context, the UE MAC layer generates the SR. The UE has a variable denoted as *UE_state* that indicates at which state is the transmission of the SR. *UE_state* is initialized to INACTIVE when the UE is created in the simulation. When the MAC layer generates the SR, it changes the value of *UE_state* from INACTIVE to TO_SEND. At the beginning of each slot, the MAC layer checks if *UE_state* is equal to TO_SEND. In this case, the MAC layer sends the SR to the PHY layer, and *UE_state* is set to ACTIVE. The PHY layer then transmits the SR to the gNB in the radio resources reserved for the Physical UL Control Channel (PUCCH) through the radio channel.

The gNB checks at each slot if control messages from the UEs are received. If an SR is received from a UE, the PHY layer saves the SR information (the Radio Network Temporary Identifier (RNTI) and BWP id) and sends the SR to the gNB MAC layer. The MAC layer takes then a scheduling decision (it decides the radio resources that are assigned to the UE) and generates the grant message to inform the UE about the allocated resources. The grant message is sent to the gNB PHY layer. The PHY layer transmits the grant to the UE in the radio resources reserved for the transmission of the Physical DL Control Channel (PDCCH). When the UE receives the grant, it prepares the allocated resources for the transmission of the data packet. The UE MAC stores the data packet to be transmitted in the allocated resources through the ProcessUlDci function. If all the data is transmitted in the current packet, the *UE_state* is set to INACTIVE. If there is data pending to be transmitted in the UE buffer, the MAC layer sends, together with the data, the BSR to inform the gNB of the amount of data pending to be transmitted at the UE and request additional resources for a new transmission. The UE PHY layer then transmits the data packet to the gNB in the allocated resources (using InsertFutureAllocation function) on the Physical UL Shared Channel (PUSCH). When the gNB receives the data packet, it checks the BSR information and takes a new scheduling decision if there is data pending to be transmitted in the UE. When the scheduling decision is taken, the gNB will be sent a new grant message to the UE. This process will be repeated as long as there is data to transmit in the UE buffer.

4. Configured Grant Implementation

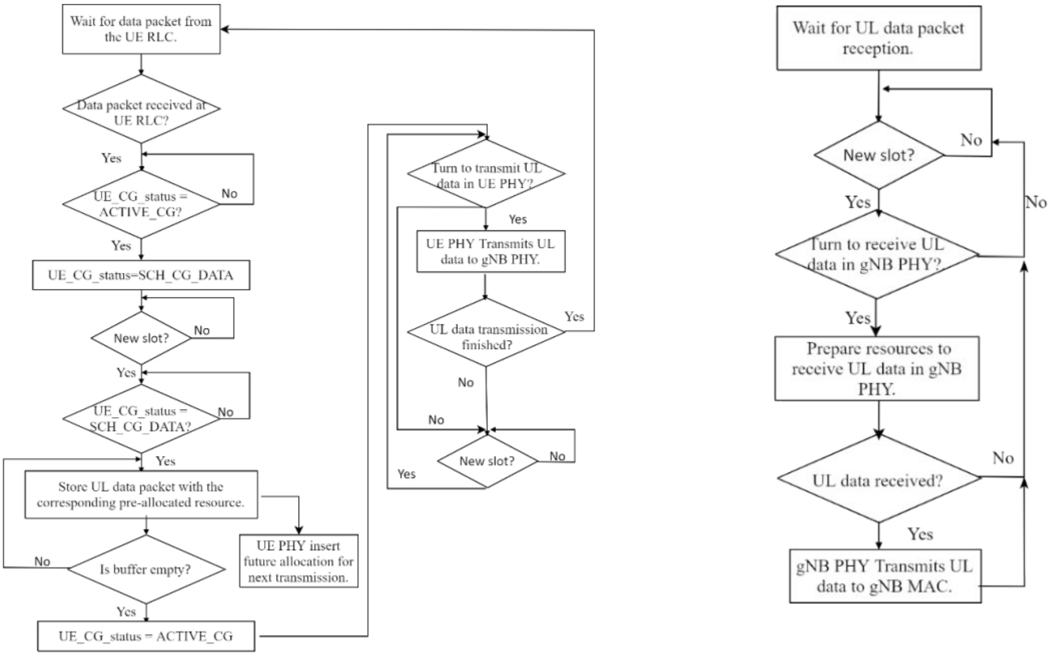
This section presents the implementation of the CG scheduling for UL transmissions carried out by the authors within 5G-LENA. In this work, we have implemented the CG Type 1 that configures the UL grant and the allocated resources when the session is established; we aim to avoid any potential transmission delay that could be introduced due to the activation/deactivation of the configured UL grant with the CG type 2 for services with very stringent latency requirements.

Fig. 2 shows a flow chart of the operation of the CG scheduling at the UE and gNB. When the simulation starts, the UEs are configured with traffic parameters such as packet size and transmission period (traffic parameters are read from the simulation configuration file). UEs that are configured to use CG scheduling have a variable referred to as *UE_CG_status* that identifies at which point of the CG configuration process is the UE. *UE_CG_status* can take the following values: INACTIVE_CG, TO_SEND_CGR, TO_RECEIVE_CG, ACTIVE_CG, and SCH_CG_DATA. *UE_CG_status* is initialized to INACTIVE_CG at the beginning of the simulation (this is shown in (Fig. 2.a). During the RRC connection establishment process, the UE sends a CG request (CGR) to the gNB. To this aim, the MAC layer generates the CGR and changes *UE_CG_status* from INACTIVE_CG to TO_SEND_CG. The MAC layer sends the CGR to the PHY layer of the UE. The PHY layer checks at the start of each slot if *UE_CG_status* is equal to TO_SEND_CG. If this is the case, it creates the control message where the CGR is transmitted and sends it to the



a) CG configuration at the UE.

b) CG configuration at the gNB.



c) Data transmission at the UE.

d) Data reception at the gNB.

Fig. 2. Operation of the CG scheduling at the UE and gNB.

gNB through the radio channel. *UE_CG_status* is set to TO_RECEIVE_CG. When the gNB receives a CGR at the PHY layer (see Fig. 2.b), the PHY layer sends the CGR message to the MAC layer. The MAC layer then decides the radio resources to be allocated to the UE; the gNB reserves the radio resources needed to transmit the packets with the required periodicity. Once the scheduling decision is taken, the MAC layer prepares the configured grant information (allocated resources and periodicity) to be transmitted to the UE and sends it to the PHY layer. The gNB PHY layer creates the control message where the CG information is transmitted and sends it to the UE through the radio channel. When the UE receives the CG, it first checks whether *UE_CG_status* is equal to TO_RECEIVE_CG (see Fig. 2.a). If this is the case, the PHY layer sends the CG information to the UE MAC layer, and the *UE_CG_status* state is changed to ACTIVE_CG. The CG information is saved at the PHY and MAC layer to be used to transmit future data packets (to this end, we use function UlData and InsertFutureAllocation in the PHY layer and ProcessUlDci in the MAC layer implemented in 5G LENA).

Once the UE receives the CG, it waits for the generation of new data. Data is generated periodically every T_p ms at the UE RLC layer. When data is received at the UE MAC layer from the RLC layer (see Fig. 2.c), the UE checks if *UE_CG_status* is equal to ACTIVE_CG. If this is the case, the MAC layer sets *UE_CG_status* to SCH_CG_DATA and stores the UL data packet with the corresponding pre-allocated resource information. Then UE MAC notifies the UE PHY layer that a new CG packet has been generated in the UE MAC. When the buffer is empty, *UE_CG_status* is changed to ACTIVE_CG. The UE PHY layer checks if the UE has pre-allocated resources in the current slot. If not, the UE PHY layer waits for the next slot. If the UE has pre-allocated resources in the current slot, the PHY layer transmits the UL data packet on the pre-allocated resources to the gNB through the radio channel. At the start of each period, the gNB prepares the PHY layer to receive a data packet on the pre-allocated resources (see Fig. 2.d). When the gNB PHY layer receives a data packet, it sends the packet to the MAC layer.

5. Validation

In this section, we validate the implementation of CG in 5G-LENA. To this end, we compare, when possible, the latency results achieved with the implemented CG in 5G-LENA with results available in the literature. In addition, we also compare the performance in terms of latency achieved using dynamic scheduling and CG. For this study, we consider a single-cell scenario with 10 MHz bandwidth at 3.55 GHz covering a typical work cell[2] of 10x10 m^2 . In the work cell, sensor UEs transmit the sensed data to a central monitoring system (only UL data). All slots in the frame are configured to be used for UL transmissions. The DL CTRL and the UL CTRL messages are transmitted in the first and last symbols of each slot, respectively. We evaluate different numbers N of sensor UEs in the scenario, with N equal to 10, 20, and 30 [13]. We consider that sensors are located at positions that guarantee Line of Sight (LOS) propagation conditions with the gNB. All UEs transmit using a robust Modulation Coding Scheme (MCS) equal to 4 (with a modulation order of 2 and a coding rate of 0.19) to guarantee a low Block Error Rate (BLER). We evaluate different numerologies, particularly, we consider numerologies (μ) 1 and 2 corresponding to a subcarrier spacing (SCS) of 30 and 60 kHz and a slot time duration of 0.5 and 0. 25 ms, respectively [2]. Following [13], the UEs transmit packets of 32 bytes with a transmission period T_p equal to 1, 5, and 10 ms. All UEs generate the packets at the same time. Packets are transmitted using 1 OFDM symbol minislot. UEs are scheduled at different symbols, and each UE receives resources in the first available symbol of the first available slot. We analyze the latency at the RLC layer that accounts for the time elapsed between the time when the UE generates the packet at the RLC layer and the time when this packet is received at the RLC layer of the gNB.

Fig. 3 shows the boxplot of the experienced latency. The top and bottom box edges represent the 10th and 90th percentile of the experienced latency, the center mark represents the median, and the plus symbol represents the maximum and minimum experienced latency values. Fig. 3.a shows the experienced latency as a function of the numerology when N=20 UEs and T_p=10 ms and CG and dynamic scheduling are used, respectively. Results in Fig. 3.a show that the latency experienced with CG decreases considerably the latency experienced when dynamic scheduling is used. For example, 75% of the transmissions experienced a latency lower than 0.9 and 0.5 ms with CG and μ equal to 1 and 2 respectively, while these values are equal to 4.4 and 2.25 ms with dynamic scheduling. This

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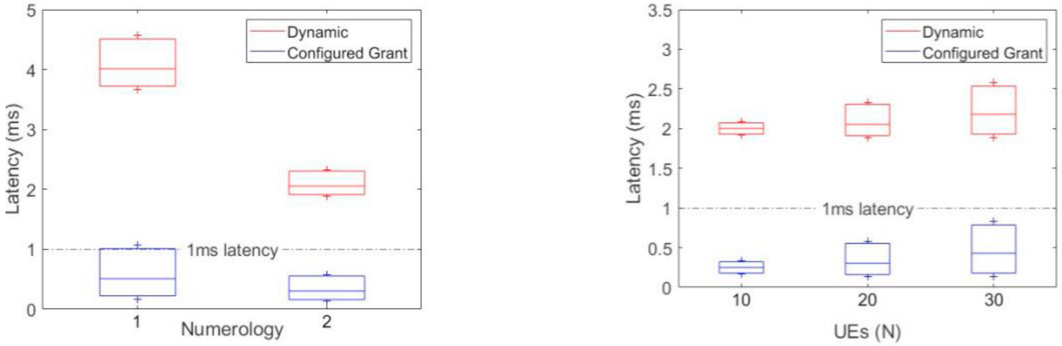
[2] The typical workcell size is 10 m x 10 m [13].

results in a reduction of 79.54 and 77.77% of the 75th percentile of the experienced latency when CG is used with μ equal to 1 and 2 respectively in comparison with the use of dynamic scheduling. The higher latency experienced with dynamic scheduling is due to the exchange of control messages to request and assign radio resources previous to the transmission of each packet. Furthermore, it is important to highlight that the latency results achieved with CG are in line with the analytical results presented in [14]. 3GPP TR 37.910 [14] evaluates the latency achievable in the radio link between the UE and the gNB when there is only one UE in the cell. It reports latency values[3] of 0.30 and 0.24 ms when using 2 OFDM symbols-minislot and μ equal to 1 and 2, respectively. The minimum latency achieved with the implemented CG in 5G-LENA is equal to 0.18 and 0.135 ms with μ equal to 1 and 2 respectively, and the latency experienced by the 25% of the transmissions is equal to 0.33 and 0. 22 ms respectively (we consider the minimum and 25th percentile of the experienced latency achieved with the implemented CG for comparison with results in [14] since these values correspond to the UE to which resources are first allocated and the evaluation conditions for these UEs are similar to when unloaded scenarios are considered). These results validate our implementation of the CG within 5G-LENA.

Fig. 3.a also shows that the latency experienced with both the dynamic scheduling and CG reduces when numerology increases. It is possible to observe that the latency experienced with μ=2 decreases by approximately 50% compared with the use of μ=1. This is because the time duration of the symbol and the slot decreases by a factor of 2 when numerology increases from 1 to 2.

As presented in [13], closed-loop applications in Industry 4.0 demands a maximum latency of 1 ms. Fig. 3.a shows that the dynamic scheduling can not meet the 1 ms latency requirement in the evaluated conditions. The minimum latency experienced by a UE with dynamic scheduling is equal to 1.89 ms when μ=2 is used. When CG is used, the 1 ms latency requirement can be satisfied using both μ equal to 1 and 2. All transmissions are performed in less than 0.58 ms when μ=2, and 90% of the transmissions are performed in less than 1 ms when μ=1.



a) Latency as a function of the numerology (N=20 UEs, T_p=10 ms). b) Latency as a function of the number of UEs (N) (μ = 2, T_p=10 ms).

Fig. 3. Experienced latency with dynamic scheduling and CG.

Fig. 3.b shows the latency experienced by the packets when the number of UEs increases. The results in Fig. 3.b correspond to μ=2 since it is the one that allows achieving the lower latency values with both dynamic scheduling and CG. Fig. 3.b shows that the minimum latency value remains equal to 0. 135 ms for all values of N. This is because the minimum value corresponds to the UE that receives resources at the first symbol of the first slot after the packets are generated, and this results in the same latency value for all values of N. However, the mean, 75th percentile, and maximum latency values increase with the increase of UEs. This is because the transmission of the UEs that receive resources in the last position is delayed more, and this increases the latency that these UEs experience.

We have also evaluated the experienced latency for different values of T_p equal to 1, 5, and 10 ms when N=20 UEs and μ is equal to 1 and 2. The results show that the same latency values are achieved for given numerology independently of the T_p when CG is used. This is because all packets can be transmitted before the next packet is generated for the UEs. With dynamic scheduling, the latency experienced when μ=2 is equal for all values of T_p.

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[3] These values correspond to the use of resource mapping Type B and UE capability 2.

However, it is possible to see that the latency considerably increases when μ=1 and T_p=1 ms. This is because a new packet is generated before the previous packet has been transmitted for some UEs. In this case, the new packet is queued at the transmitter, and latency considerably increases.

6. Conclusions

This paper has presented the implementation of the configured grant scheduling included in 3GPP Release 16 within the 5G-LENA 5G NR simulator. Configured grant is one of the key mechanisms to reduce communication latency and support URLLC services with stringent latency requirements from critical verticals such as manufacturing. The main features of the implemented code have been briefly described in this paper. In addition, it has also been described the integration of the code within the logical structure of the 5G-LENA simulation tool.

The configured grant implementation has been validated through system-level simulations. Furthermore, we have presented some initial evaluations about the potential to use the configured grant to support Industry 4.0 applications with stringent latency requirements to illustrate the potential of the implemented code.

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