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5G Configured Grant Scheduling for Seamless Integration with TSN Industrial Networks

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ABSTRACT

The integration of 5G (5th Generation) and TSN (Time Sensitive Networking) networks is key for the support of emerging Industry 4.0 applications, where the flexibility and adaptability of 5G will be combined with the deterministic communications features provided by TSN. For an effective and efficient 5G-TSN integration both networks need to be coordinated. However, 5G has not been designed to provide deterministic communications. In this context, this paper proposes a 5G configured grant scheduling scheme that coordinates its decision with the TSN scheduling to satisfy the deterministic and end-to-end latency requirements of industrial applications. The proposed scheme avoids scheduling conflicts that can happen when packets of different TSN flows are generated with different periodicities. The proposed scheme efficiently coordinates the access to the radio resources of different TSN flows and complies with the 3GPP (Third Generation Partnership Project) standard requirements.

1. Introduction

Industry 4.0 aims to digitalize conventional industries, transforming them into intelligent, adaptable factories that optimize resource utilization and provide innovative, efficient, and error-free services [1]. This digitalization requires complete factory connectivity where cutting-edge technologies such as augmented reality and cooperative mobile robots play a critical role. These technologies require highly reliable, deterministic, low latency, and easily adaptable communications to function effectively. Nowadays, wired Time Sensitive Networking (TSN) is used in factories to support communications with these stringent requirements [2]. However, the use of wireless networks becomes essential to support mobile devices and adaptable industrial environments, enabling alignment with the evolving demands of the factory. 5th Generation (5G) networks have been developed to provide low latency and highly reliable communications. Nonetheless, 5G has not been designed to offer deterministic communications. To achieve the level of flexibility required by the factories while ensuring the deterministic communications demanded by industrial applications, the efficient and effective integration of 5G and TSN networks is necessary. To achieve this, the operation of both networks must be coordinated. The management of TSN data packets within the 5G network is crucial for this coordination, which is handled by the scheduling scheme in 5G.

Industrial applications predominantly generate periodic and deterministic traffic [3] that is best supported in 5G by the semi-static scheduling (e.g. [4, 5]), known as Configured Grant (CG) in the uplink (UL) and Semi-Persistent Scheduling (SPS) in the downlink (DL). These mechanisms allocate periodic radio resources to users (UE) and base stations (gNB) in advance, enabling them to transmit data immediately, upon data generation, on the preassigned resources. This approach eliminates the need to request radio resources for each packet transmission and reduces the latency. Current proposals to coordinate 5G and TSN schedulers handle each TSN flow grant separately, which can lead to scheduling conflicts when the TSN flows have different periodicities. Figure 1 illustrates a scenario where the 5G scheduler assigns an individual grant or CG configuration for each TSN flow. This scenario involves two TSN flows with different periodicities (p_1 and p_2). Scheduling conflicts can occur when both TSN flows share the same radio resources at a given time due to their different periodicities (Figure 1). In our previous works [6] and [7], we addressed this issue with two scheduling schemes: one based on optimization techniques and the other on a heuristic algorithm. Both schemes are designed to manage TSN traffic in the 5G network and prevent scheduling conflicts by generating all the needed grants for each TSN flow, ensuring that each grant repeats periodically with a period equal to the minimum common periodicity of all transmitting TSN flows. However, these works do not comply with the limitation imposed by the Third Generation Partnership Project (3GPP) standard regarding the maximum number of CG configurations that can be assigned to a UE, which is 12 CGs per UE [8].

In this context, this work focuses on TSN flow management within the 5G network to ensure proper coordination with the TSN network and prevent conflicts between TSN flows with different periodicities. To achieve this, we propose a novel scheduling scheme that assigns multiple CG configurations to each TSN flow associated with a UE, while limiting the number of CG configurations per TSN flow in accordance with the 3GPP standard. To comply with this limitation, the proposed scheduling scheme allows to

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assign CG configurations to different TSN flows or UEs (each TSN flow is supported by a different UE) that may pre-allocate the same radio resources at certain times, which result in potential conflicts. To coordinate the access of different UEs to shared resources for the transmission of TSN packets, the proposed scheme defines an activation vector associated with each CG configuration. This vector indicates whether the UE is permitted to access the pre-allocated radio resources each time a new packet must be transmitted. The activation vector contains a number of elements equal to the number of packets each UE will transmit within a specified time interval. Each element assumes a value of 1 if the UE has permission to access the radio resources pre-allocated by the CG configuration, or 0 if access is not permitted. Using this vector, the UE can identify which CG configuration is active for the transmission of each TSN packet without the need to exchange messages with the gNB; only one CG configuration is active for the transmission of each packet for a UE. Consequently, this vector also reduces the signaling messages required for activating CG configurations, enabling UEs to access the radio resources in a coordinated manner avoiding scheduling conflicts with other UEs (or TSN flows), thereby reducing the number of generated CG configurations. This article also proposes how this vector could be included in the 3GPP specifications to be compliant with the standard.

The rest of the paper is structured as follows. Section 2 explains the most important 5G-TSN integration and 5G configured grant scheduling scheme features. Section 3 introduces the state of the art on scheduling schemes in integrated 5G-TSN networks. Section 4 presents the proposed 5G scheduler to manage TSN packets, while Sections 5 and 6 explain the reference scheduling schemes used for comparison and the evaluated scenario, respectively. Section 7 evaluates the proposed scheduler and compares it with the reference scheduling schemes. Finally, Section 8 concludes the paper.

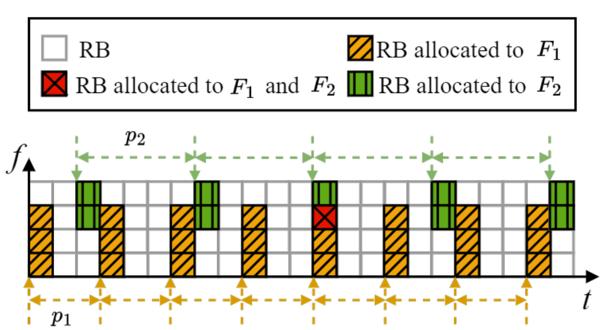

Figure 1: Scheduling conflict when two TSN flows with different periodicities share the same radio resources at a certain time.

2. 5G-TSN Integration Model

TSN has been developed as an extension of the Ethernet link layer to support deterministic transmissions with real-time and high-reliability requirements [9] . A TSN network is composed of end devices (e.g. controllers and robots) that transmit TSN flows via TSN bridges. A TSN bridge works as a special Ethernet switch with the ability to determine the time intervals during which it can forward a packet to the next device. The time intervals are defined by the TSN scheduling. Based on 3GPP [10], 5G is going to be integrated within a fully centralized TSN network as a virtual TSN bridge. A virtual 5G bridge implements TSN translators (TT) on each input/output port for working as points of connection between 5G and TSN. The Device-Side TSN Translators (DS-TT) are implemented on ports corresponding to UEs, while the Network-Side TSN Translators (NW-TT) are implemented on ports corresponding to the 5G Core Network (CN).

The fully centralized TSN network uses Centralized User Configuration (CUC) and Centralized Network Configuration (CNC) to configure the complete 5G-TSN network. First, the TSN bridges, as well as the virtual 5G bridge, send their capabilities to the CNC. The application requirements are transmitted from the end devices to the CUC and forwarded to the CNC. The CUC may modify the traffic requirements before transmitting them to the CNC. When the CNC receives all the information, it calculates the path over which each TSN flow should be transmitted and determines the time intervals for packet forwarding between bridges (i.e. the TSN scheduling). Then, the CNC transmits this information to each bridge as TSN configuration commands. After receiving the CNC commands, the virtual 5G bridge must schedule the packets to coordinate with the wired TSN network. The scheduling of different TSN flows must be done so that they align with the specified arrival and departure times of the packets to the virtual 5G bridge. This information is defined by the CNC, and it is mapped to Time Sensitive Communication Assistance Information (TSCAI) and 5G Quality of Service (QoS) information. TSCAI and 5G QoS parameters are used to perform the scheduling in 5G. TSCAI informs about the packet arrival time to the input port of the virtual 5G bridge, flow direction (UL or DL), packet periodicity, and survival time (i.e. the time that an application can work correctly without receiving a packet) for each TSN flow. The 5G QoS profile defines the resource type, flow's priority level, Maximum Data Burst Volume (MDBV), required Packet Error Rate (PER), and the Packet Delay Budget (PDB), which indicates the maximum latency that a packet can experience within the 5G network.

2.1. 3GPP 5G Configured Grant Scheduling

5G introduces CG and SPS in addition to the use of dynamic scheduling for UL and DL, respectively. CG and SPS eliminate the need to request radio resources for each packet (as it is done with dynamic scheduling). With CG and SPS, radio resources are allocated periodically to gNBs or UEs, respectively, before data packets are generated, and this allocation is repeated with a given periodicity. When a data packet is generated, it can be transmitted using the pre-allocated resources eliminating the need for signaling exchange between the UE and gNB.

In 5G New Radio (NR), a radio resource is equal to a Resource Block (RB) in the frequency domain and an Orthogonal Frequency Division Multiplexing (OFDM) symbol in the time domain. An RB contains 12 consecutive subcarriers in the frequency domain. A slot consists of 14 OFDM symbols when using the Normal Cyclic Prefix (CP). The Sub-Carrier Spacing (SCS) and the slot duration depend on the numerology (μ), being $\mu = \{0, 1, 2, 3, 4, 5, 6\}$ which corresponds to SCS = $15{\cdot}2\mu$ kHz and $1/2^{\mu}$ ms slot duration [11].

Focusing on UL transmissions, two types of CG can be used. Type 1, which is configured by Radio Resource Control (RRC) signaling and it is activated from the moment it is set up through RRC, and Type 2, where the CG is configured by RRC and Downlink Control Information (DCI) and it is activated or deactivated using DCI signaling. The period for both types is configured in RRC and the resources to be used are configured by DCI for type 2, but the way to calculate the resources to be used is the same for both types. Through CG configuration message, the gNB informs the UE of the first allocated radio resource and the periodicity of the allocated resources (*periodicity*). To indicate the first allocated radio resource, the gNB determines the *timeReferenceSFN*, *timeDomainOffset*, and *S* to identify the first allocated frame, slot, and symbol within the slot, respectively. Then, the UE knows which radio resources to use for each packet transmission based on the expression (1) given in [12] and, the information provided by the CG configuration. This expression determines the allocated radio resources for the N^{th} packet ($N \geq 0$) of the TSN flow.

$$\begin{aligned}
&[\,(\mathrm{SFN}{\cdot}\mathrm{n}\mathit{SlotsPerFrame}{\cdot}\mathit{nSymPerSlot}) \\
&+ (\text{slot number in the frame}{\cdot}\mathit{nSymPerSlot}) \\
&+ \text{symbol number in the slot}] = \\
&(\mathit{timeReferenceSFN}{\cdot}\mathit{nSlotsPerFrame}{\cdot}\mathit{nSymPerSlot} \\
&+\mathit{timeDomainOffset}{\cdot}\mathit{nSymPerSlot} + S + N{\cdot}\mathit{periodicity}) \\
&\mathrm{modulo}(1024{\cdot}\mathit{nSlotsPerFrame}{\cdot}\mathit{nSymPerSlot})
\end{aligned} \tag{1}$$

The names of variables have been shortened to simplify reading the equation (1) (e.g., *numberOfSlotPerFrame* in [12] is called *nSlotSPerFrame* in this paper). In (1), *nSlotsPerFrame* and *nSymPerSlot* represent the number of slots in a frame (a frame has a duration of 10 ms) and the number of symbols in a slot, respectively. *nSlotsPerFrame* is equal to 10·1 slots when $\mu = 0$ and equal to 10·16 slots for $\mu = 4$, while *nSymPerSlot* depends on the number of symbols in the slot. Therefore, to transmit the N^{th} packet, the UE uses the radio resources defined by the parameters: System Frame Number (SFN), slot number in the frame, and symbol number in the slot. A UE can receive several CG configurations. 3GPP limits the number of CG configurations assigned to a UE to a maximum of 12 configurations in a Bandwidth Part (BWP) [8]. A BWP is defined as a set of consecutive RBs with specific numerology on a given carrier.

3. State of the Art

The coordination of the 5G and TSN schedulers is key to achieve their effective and efficient integration and meet the requirements of Industry 4.0 applications. In the literature two main approaches can be identified for this integration. Firstly, some works are proposing to address the scheduling problem in the TSN network together with packet scheduling in the 5G network. These works formulate an optimization problem for joint 5G-TSN scheduling considering the constraints that both networks must meet [13, 14, 15]. However, jointly addressing the scheduling in both networks entails a high computational time. For this reason, other studies propose to execute the scheduling of the TSN and the 5G networks in a coordinated manner (and not integrated), meaning they consider shared information between both networks. In this case, firstly, the scheduling of the TSN network is performed considering the capabilities of the 5G network. Subsequently, the 5G network will schedule the transmission of TSN packets over the radio channel to align with the TSN schedule previously determined by the CNC. In this context, several studies focus on the development of the 5G scheduler to properly manage TSN flows [4, 5, 16, 17, 18].

Most of the aforementioned works highlight that CG and SPS are the optimal scheduling mechanisms to support TSN traffic within the 5G network. In the case of UL transmissions, a UE may have multiple CG configurations to support various services or enhance communication reliability. When the packet generation time is unknown or uncertain, [19, 20] propose creating multiple CG configurations with different *timeDomainOffset* for the same UE, and the UE can select the closest CG configuration to start transmitting a packet without waiting for the next period. The work in [21] also proposes to assign multiple CG configurations to a UE generating aperiodic traffic and studies a scheme to select the optimal CG for each packet transmission that better meets both latency and reliability requirements. Periodic TSN traffic is studied in [5]. Specifically, [5] investigates how to tackle the problem that arises when the periodicity of TSN traffic differs from the periodicities of radio resource allocation that can be configured using CG in 5G NR. [5] proposes to assign multiple CG configurations to each TSN traffic. The UE will select the CG for each packet transmission to fulfill the required latency.

When we focus on periodic TSN traffic, previous proposals result in the allocation of periodic radio resources for each TSN flow. Therefore, the same radio resources can be allocated to different TSN flows if the periodicities of different CGs are not multiples of each other. This can lead to simultaneous transmission attempts by different flows, thereby creating a scheduling conflict or packet collision (see Figure 1). A predictive scheduler is proposed in [22] to avoid conflicts between resource allocations of different SPS configurations with different periodicities. It divides the bandwidth into different consecutive sets of RBs, allowing only one SPS configuration within each set to avoid scheduling conflicts between different SPS configurations. The study in [23] proposes to optimize the number of created CG configurations considering multiple periodicities, but specific details on its operation are not provided. In [6] and [7], we propose two CG scheduling schemes for managing TSN traffic in the 5G network, one is based on optimization policies, and the other one is a heuristic algorithm. Both solutions are designed to avoid collisions between packets with different periodicities, maximize the number of supported TSN flows, and minimize the latency. However, both proposals may generate a higher number of CG configurations than the limit imposed by the 3GPP [8] (12 CG configurations per UE).

4. 5G NR CG Scheduling for TSN Traffic

This section presents a novel 5G scheduling scheme that aims to guarantee the latency and deterministic requirements of the maximum number of TSN flows in an integrated 5G-TSN network. The proposed scheduling scheme exploits the information transmitted by the CNC to avoid scheduling conflicts among TSN flows with different periodicities. To this end, it can configure several CGs for each TSN flow. The proposed scheme considers the maximum number of CGs that can be configured per UE. To avoid exceeding the established maximum number, the scheme proposes the use of an activation vector for each CG, enabling the activation and deactivation of various CGs configured for each flow. This approach helps to avoid conflicts while satisfying the maximum number of CG configurations that can be assigned to a UE following the 3GPP standard and it also reduces the signaling messages between the gNB and the UEs. The proposed scheme assigns, whenever possible, the same CG configuration to packets of the same TSN flow. In this way, it is possible to reduce the total amount of CG configurations required for a single TSN flow, respecting the limit set by 3GPP [8]. The proposed new scheduling scheme has been named Heuristic 3GPP-Compliant Flexible configured grAnt Scheduling for TSN traffic (C-FAST).

In an integrated 5G-TSN network, CNC determines the arrival and the departure times of each TSN flow at each bridge. Given the maximum latency that each TSN flow must experience in the 5G network (l_i^{5G}), C-FAST allocates radio resources to ensure packets are received at the output port of the virtual 5G bridge before the departure time specified by the CNC. We consider N_F TSN flows are transmitted through the virtual 5G bridge. Each TSN flow F_i (with i=1,..,N_F) transmits packets with size $size_i$ bytes every p_i ms period. The packet $size_i$ and p_i can be different for each TSN flow. Each packet demands d_i radio resources. The packets to be transmitted in a TSN flow F_i are represented as $pkt_{i,j}$ where i indicates the TSN flow F_i and j indicates the packet number within TSN flow F_i (being $j \geq 1$). The arrival and departure times of a packet $pkt_{i,j}$ are given by $A_{i,j} = A_i + (j-1) \cdot p_i$ and $D_{i,j} = A_{i,j} + l_i^{5G}$, respectively, being A_i the arrival time of the first packet of flow F_i. The packet processing time in the UE and gNB are represented by $t_{UE,tx}$ and $t_{gNB,rx}$, respectively.

4.1. Activation Vector

To avoid a scheduling conflict (Figure 1), we propose the use of an activation vector in order to coordinate the access to radio resources allocated to more than one TSN flow. The proposed activation vector is defined for a period of time called *Period* and the number of elements of the vector is equal to the number of packets for a TSN flow within *Period* (N_{pkt}^i). Each element can take a value equal to 1 or 0. When the j^{th} element of the vector is equal to 1 (with j=1,..,N_{pkt}^i), it means that this CG configuration is used to transmit the j^{th} packet. If the value of the j^{th} element of the vector is equal to 0, this CG configuration is not used for the transmission of the j^{th} packet.

We define a CG configuration assigned to a TSN flow as $CG_{c_i}^i = \{s_{0,c_i}^i, p_{c_i}^i, V_{c_i}^i\}$, where s_{0,c_i}^i indicates the first symbol assigned to the first packet of the TSN flow F_i within *Period* (with $s_{0,c_i}^i \geq 1$), $p_{c_i}^i$ indicates the periodicity at which the radio resource reservation is repeated, and $V_{c_i}^i$ is the activation/deactivation vector. The parameter c_i is the cardinal that identifies the CG configuration assigned to the TSN flow F_i and it can take a value from 1 to the number of CG configurations assigned to that flow (limited to 12). The first symbol assigned to the N^{th} packet of the TSN flow F_i is calculated as: $s_{N,c_i}^i = (s_{0,c_i}^i + N \cdot p_{c_i}^i) \cdot V_{c_i}^i$. The parameter $p_{c_i}^i$ is equal to the periodicity p_i at which the packets of TSN flow F_i arrive at the virtual 5G bridge. The vector is defined as $V_{c_i}^i = \{a_{c_i,j}^i\}$ and j can be related to N as $j = N + 1 - N_{pkt}^i \cdot \lfloor \frac{N}{N_{pkt}^i} \rfloor$.

The use of the activation vector is illustrated in Figure 2. Figure 2.a shows an example of radio resource allocation to different TSN flows. The arrival times of the packets of the TSN flow F_1 are represented by an arrow, and their d_1 radio resource assignment is represented by different colors; each color represents the radio resource allocation for a different CG configuration. The radio resources in gray are assigned to other flows different from flow F_1. In this example, the TSN flow F_1 has received two CG configurations as illustrated in Figure 2.b and 2.c: $CG_1^1 = \{2, 3, [110]\}$ represented with green color and $CG_2^1 = \{3, 3, [001]\}$ represented with blue color. While the 1^{st} and 2^{nd} packets of F_1 are transmitted using the radio resources indicated in the CG_1^1 configuration, the 3^{rd} packet is transmitted based on the radio resources stated by CG_2^1 configuration.

The activation vector is established by the gNB taking into account the radio resources allocated for all the TSN flows, and it is sent to the UE together with the periodicity $p_{c_i}^i$ and the information about the first assigned OFDM symbol s_{0,c_i}^i. The UE uses this data to determine the allocated radio resources for the transmission of each packet. To this end, the UE will use the following expression:

$$\begin{aligned}
&[\,(\text{SFN}\cdot\text{n}\textit{SlotsPerFrame}\cdot\textit{nSymPerSlot}) \\
&+ (\text{slot number in the frame}\cdot\textit{nSymPerSlot}) \\
&+ \text{symbol number in the slot}] = \\
&[(\textit{timeReferenceSFN}\cdot\textit{nSlotsPerFrame}\cdot\textit{nSymPerSlot} \\
&+\textit{timeDomainOffset}\cdot\textit{nSymPerSlot} + S + N\cdot\textit{periodicity}) \\
&\text{modulo}(1024\cdot\textit{nSlotsPerFrame}\cdot\textit{nSymPerSlot})]\cdot a_{c_i,j}^i
\end{aligned} \tag{2}$$

The expression in (2) incorporates the activation vector to (1) to indicate which CG configuration is used for the transmission of each packet of the TSN flow F_i. The activation vector allows better and more efficient coordination for accessing radio resources across multiple UEs. It also minimizes signaling between the UE and the gNB when activating or deactivating the CG configurations for each UE. Expression (2) incorporates into expression (1) the component $a^i_{c_i,j}$ of the vector $V^i_{c_i}$. $a^i_{c_i,j}$ corresponds to the packet $pkt_{i,j}$ of the flow F_i within *Period*. As j can be related to N, $a^i_{c_i,j}$ corresponds to packet N. When a UE has to transmit a new packet, it calculates the s^i_{N,c_i} for all c_i defined by flow F_i. Then, the UE will use the resources allocated by $CG^i_{c_i}$ only if $a^i_{c_i,j} = 1$. In Figure 2, for $N = 5$, $s^1_{5,1} = (2+5\cdot 3)\cdot a^1_{1,2} = 17\cdot 0 = 0$ and $s^1_{5,2} = (3+5\cdot 3)\cdot a^1_{2,2} = 18\cdot 1 = 18$, then $d_1 = 2$ radio resources in OFDM symbol 18, determined by CG^1_2, are used to transmit the $N = 5$ packet.

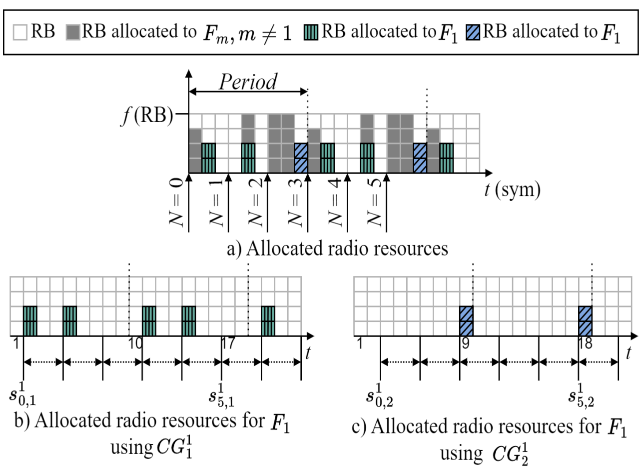

Figure 2: Example of the CG configuration definition and the use of the activation vector.

4.2. C-FAST

The operation of C-FAST is described in Algorithm 1. First, the duration of *Period* is calculated considering the packets arrival pattern that is repeated over time. This pattern is calculated as the least common multiple of the transmitted packets periodicities in each TSN flow F_i and it is called *Hyperperiod* or *HP*, i.e., *HP*=lcm(p_i) and *Period* = *HP*. Since the packet arrivals to the virtual 5G bridge repeat every *HP*, C-FAST allocates radio resources to packets within the first *HP*. The scheduling solution achieved for the first *HP* is repeated in the following periods of duration *HP*.

In order to reduce the computational time, C-FAST divides the scheduling problem into several sub-problems (line 1 in Algorithm 1). To this end, it separates the packets within *HP* in G_z groups (with $z = 1,..,N_G$). Each group contains the packets whose transmission could overlap in time according to their arrival and departure time to the 5G network. The maximum departure time of packet $pkt_{i,j}$ is equal to $A_{i,j} + l^{5G}_i$. Then, two packets $pkt_{i,j}$ and $pkt_{m,n}$ from different flows F_i and F_m can overlap if $A_{i,j} \leq A_{m,n} \leq A_{i,j} + l^{5G}_i$ or $A_{i,j} \leq A_{m,n} + l^{5G}_m \leq A_{i,j} + l^{5G}_i$.

C-FAST performs the allocation of radio resources to the packets contained in each G_z group separately. First, it calculates the number d_i of radio resources required by each packet based on the Modulation and Coding Scheme (MCS) to be used (see equation (3)). The amount of data to transmit is calculated as the sum of the Transport Block Size (TBS) and the Cyclic Redundancy Check (CRC). The TBS (in bytes) is the smallest size in table 5.1.3.2 of [24] capable of transmitting a packet of $size_i$+*header*, where the *header* refers to the Ipv4 header. The MCS is defined by the coding rate R and the modulation order Q_m. $N_{sc,RB}$ is the number of subcarriers within an RB in the 5G NR grid which is equal to 12. Once d_i is known, C-FAST calculates the number d^S_i of OFDM symbols and the number d^R_i of RBs it must allocate to each packet in the TSN flow F_i to satisfy the demanded radio resources d_i.

$$d_i = \left\lceil \frac{[tbs_i(size_i+header)+CRC]\cdot 8}{R\cdot Q_m\cdot N_{sc,RB}} \right\rceil \tag{3}$$

In order to minimize the experienced latency, we consider that the number of symbols allocated for packet transmission is the minimum possible based on d_i. Therefore, it allocates $d^R_i = d_i$ RBs in an OFDM symbol ($d^S_i = 1$ with t_{sym} ms OFDM symbol duration) when d_i is less than the number of RBs available in the bandwidth (R_{BW}), i.e., when $d_i \leq R_{BW}$. Whereas, if $d_i > R_{BW}$, C-FAST will assign $d^R_i = R_{BW}$ RBs in $d^S_i = \lceil d_i/R_{BW} \rceil$ OFDM symbols.

Subsequently, C-FAST tries to find a scheduling solution in which all packets in the G_z group receive radio resources for transmission while meeting their latency requirements l^{5G}_i. To reduce the amount of created CG configurations, C-FAST tries to serve the maximum number of packets of a TSN flow F_i using the same CG configuration. In this context, C-FAST allocates radio resources for each packet within G_z group through an iterative process (lines 6-34 of Algorithm 1). In the first iteration, C-FAST goes through all the TSN flows in G_z according to their latency requirements l^{5G}_i from lowest to highest (lines 8-11 of Algorithm 1). For each TSN flow F_i, C-FAST allocates to the first packet the first available d^R_i RBs in d^S_i consecutive symbols after the packet is received in the UE and it is processed ($A_{i,j}$+$t_{UE,tx}$). Based on the allocated resources, C-FAST creates CG^i_1 and reserves radio resources periodically with a periodicity equal to $p^i_{c_i}$ (line 5 of Algorithm 2) for this TSN flow. C-FAST checks if other packets of the same TSN flow F_i can be transmitted using CG^i_1, i.e., it checks if the radio resources reserved with CG^i_1 for the transmission of the j^{th} packet have been allocated to a different TSN flow previously (lines 15-24 of Algorithm 2). If this is the case, the $a^i_{c_i,j}$ element of the activation vector is set to 0, and to 1 otherwise (line 19 of Algorithm 2). The packets of the TSN flow F_i that can be transmitted with the radio resources indicated in the CG^i_1 configuration are removed from G_z.

After going through all the TSN flows in G_z, C-FAST checks if there are packets within G_z that have not allocated radio resources (lines 11-14 of Algorithm 1). If this is the case, C-FAST selects the packet within G_z with the most

Algorithm 1: C-FAST Scheduling

Input : TSN flows $F_i\ \forall i$
Output: Created $CG^i_{c_i}\ \forall i, c_i$
1 Calculate HP and create G_z groups
2 **for** $z \leftarrow 1$ *to* N_G
3   Calculate d_i^R and d_i^S for each packet in G_z
4   Initialize $iter = 0, GF_z = \emptyset, m = \{i\}, c_i = 1\ \forall i$ in G_z
5   N_{pkt} = number of packets in G_z
6   **while** $iter < \infty$
7   **while** $(m \neq \emptyset) \mid (G_z \neq \emptyset)$
8   **if** $m \neq \emptyset$
9         $pkt_{i,j}$ = first packet with lower l_i^{5G} in G_z with $i \in m$
10         $m = m - \{i\}$
11   **else**
12         $pkt_{i,j}$ = first packet with lower l_i^{5G} in G_z
13   Find new CG for F_i (c_i++)
14   **end**
15       $[G_z, CG^i_{c_i}, N_{pkt}, GF_z]$ = NewCG (Algo. 2)
16   **if** $CG^i_{c_i} = \emptyset$
17         $iter$++ and Goto line 20
18   **end**
19   **end**
20   **if** $CG^i_{c_i} = \emptyset$
21   **if** *number of packet in* $GF_z + G_z = N_{pkt}$
22   Goto line 35
23   **else**
24         $GF_z = GF_z + \{pkt_{i,j}\}$
25   Reinitiate G_z and N_{pkt}
26         $G_z = G_z - GF_z$
27   Free allocated resources to packets in G_z
28   Update all $CG^i_{c_i}$ (erase $CG^i_{c_i}$ if $V^i_{c_i} = \emptyset$)
29   Goto line 13
30   **end**
31   **else**
32   Goto line 35
33   **end**
34   **end**
35   **if** $G_z \neq \emptyset$
36   No feasible, then stop scheduling, Goto line 38
37   **end**
38 **end**

Algorithm 2: New CG

Input : $pkt_{i,j}, c_i, G_z, d_i^R$ and d_i^S
Output: $G_z, CG^i_{c_i}, N_{pkt}, GF_z$
1 Initialize $G_{aux} = \emptyset$
2 s_{aux} = first OFDM symbol after $A_{i,j} + t_{UE,tx}$
3 **while** $(s_{aux} + d_i^S - 1) \cdot t_{sym} \leq A_{i,j} + l_i^{5G} - t_{gNB,rx}$
4   **if** *there are free* d_i^R *RBs in* s_{aux} *until* $s_{aux} + d_i^S - 1$ *symbols*
5   Create $CG^i_{c_i} = \{s^i_{0,c_i}, p^i_{c_i}, V^i_{c_i}\}$ with $s^i_{0,c_i} = s_{aux} - (j-1) \cdot p_i, p^i_{c_i} = p_i, a^i_{c_i,j} = 1$ and $a^i_{c_i,m} = 0, \forall m \neq j$
6     $G_z = G_z - \{pkt_{i,j}\}$
7   Goto line 15
8   **else**
9   s_{aux}++
10   **end**
11 **end**
12 **if** $(s_{aux} + d_i^S - 1) \cdot t_{sym} > A_{i,j} + l_i^{5G} - t_{gNB,rx}$
13   $CG^i_{c_i} = \emptyset$ and Goto line 30
14 **end**
15 **while** *there are* F_i *packets in* G_z
16   $pkt_{i,j}$ = packet from F_i with lower $A_{i,j}$ in G_z
17   $s_{aux} = s^i_{0,c_i} + (j-1) \cdot p^i_{c_i}$
18   **if** *there are free* d_i^R *RBs in* s_{aux} *until* $s_{aux} + d_i^S - 1$ *symbols*
19   Update $V^i_{c_i}$ with $a^i_{c_i,j} = 1$
20   **else**
21     $G_{aux} = G_{aux} + \{pkt_{i,j}\}$
22   **end**
23   $G_z = G_z - \{pkt_{i,j}\}$
24 **end**
25 **if** $(s^i_{0,c_i} + d_i^S - 1) \cdot t_{sym} = A_{i,1} + l_i^{5G} - t_{gNB,rx}$
26   $GF_z = GF_z +$ {the $pkt_{i,j}$ packets in F_i with $a^i_{c_i,j} = 1\ \forall j$}
27 **else**
28   $N_{pkt} = N_{pkt} -$ (number of packets in F_i with $a^i_{c_i,j} = 1\ \forall j$)
29 **end**
30 $G_z = G_z + G_{aux}$

restrictive l_i^{5G} that arrives first at the virtual 5G bridge. Then, C-FAST allocates the first available radio resources to this packet following Algorithm 2 and creates a new $CG^i_{c_i}$ configuration. Then, it checks whether the rest of the packets of the same TSN flow F_i can be transmitted using $CG^i_{c_i}$ configuration. If yes, the activation vector is updated, otherwise, this packet is added again to the G_z group. This process is repeated until all packets of all TSN flows included in G_z group have a CG configuration assigned to them.

If it is not possible to allocate radio resources to a packet $pkt_{i,j}$ complying with the latency requirement (lines 12-14 of Algorithm 2), C-FAST tries to find a different solution that can serve all the packets of all TSN flows. To this end, the proposed scheduling restarts the scheduling process (executes a new iteration). Only those packets that received radio resources just before the deadline will maintain the radio resources previously allocated. When this happens, these packets are included in the GF_z group (line 26 in Algorithm 2). Then, at the beginning of a new iteration, C-FAST reestablishes the initial group G_z of packets. From this initial group, it deletes the packets included in GF_z (lines 25-26 in Algorithm 1). Subsequently, it deletes all the CG configurations and associated vectors for all the packets included in G_z (lines 27-28 of Algorithm 1). Consequently, the packets included in G_z must receive radio resources again. In this new iteration, the first packet to receive resources will be the packet that could not receive radio resources in the previous iteration, which is also included in the GF_z group. The rest of the packets will be attended in order based on their latency requirement l_i^{5G}. Once C-FAST finds a solution that meets the requirements of all packets in the current G_z group, it starts allocating resources for the packets of the next G_z group. The scheduling process is finalized either when there is no feasible solution to the problem (i.e. there are not enough radio resources available to allocate all packets meeting their latency requirements) or when all the packets in the HP are scheduled.

5. Reference Schemes

The study reported in [6] proposes O-FAST (Optimum Flexible configured grAnt Scheduling for TSN traffic), a 5G CG scheduling scheme that uses optimization processes to increase the number of TSN flows supported within the 5G network while reducing the experienced latency. The same objective is sought with the H-FAST (Heuristic Flexible configured grAnt Scheduling for TSN traffic) proposal in [7], but H-FAST is based on a heuristic problem and has, therefore, a lower computational time. Similarly to C-FAST, both scheduling schemes calculate the *HP* and address the scheduling for packets within *HP*; the solution achieved is repeated in successive periods of duration *HP*. Both reference schemes allocate the available radio resources that minimize the experienced latency for each packet. From the allocated resources for each packet, a new CG configuration is created that reserves radio resources with a periodicity *HP* for packets of the same flow F_i. As a result, the reference schemes generate as many CG configurations for each TSN flow as the number of TSN flow F_i packets are in *HP*. This behavior is very different from that proposed by C-FAST; C-FAST sacrifices latency in order to meet the maximum number of CG configurations that can be allocated to an UE following 3GPP standard.

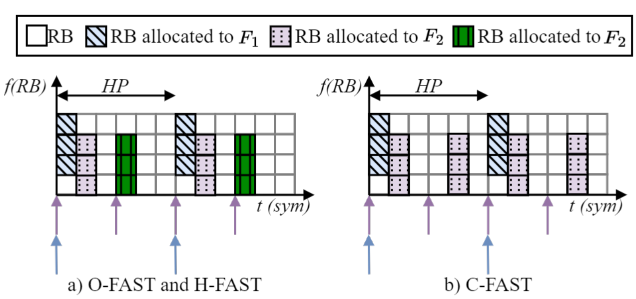

Figure 3: Example of scheduling solution when applying H-FAST, O-FAST and C-FAST.

Figure 3 illustrates the difference between O-FAST, H-FAST, and C-FAST. In this example, H-FAST and O-FAST create two CG configurations with an *HP* periodicity for flow F_1. With this resource allocation, H-FAST and O-FAST minimize the average latency experienced by packets. On the other hand, C-FAST generates a single CG configuration for both packets of TSN flow F_1 within the *HP* since it is designed with the objective of reducing the number of CG configurations. In this case, the radio resources assigned via this CG configuration are repeated with a periodicity equal to p_1, which is the rate at which TSN flow F_1 packets arrive at the virtual 5G bridge.

The proposed scheduling scheme is also compared with a common 5G configured grant scheduling scheme (referred to as reference scheme or Ref.) that is proposed and used in several works in the literature [4, 5]. This scheme creates only one CG configuration for each TSN flow F_i, and the resources are repeated with a periodicity equal to p_i (see Figure 1).

6. Evaluation Scenario

We consider a 5G private network deployed in an industrial plant that must coordinate its operation with a TSN network to provide connectivity for a closed-loop supervisory controller application. This type of application is commonly used in Industry 4.0 scenarios [25]. Within this context, sensors (S_1, S_2, ... in Figure 4) periodically transmit TSN flows containing monitoring data to a Programmable Logic Controller (PLC), which then generates commands for the actuator A. The sensors create N_F TSN flows (ranging between 10 and 30) that are transmitted to the PLC through TSN bridges and the virtual 5G bridge (in the UL direction) (see Figure 4). N_F ranges between 10 and 30 as established in [25] for Traffic Class 2 where the closed-loop supervisory of $size_i \in [40, 250]$ bytes every $p_i \in [4, 9]$ ms period, and these packets must be received at the PLC within a bounded end-to-end latency (l_i^{e2e}) which is equal to 4 ms ($size_i, p_i$, and l_i^{e2e} are established based on the characteristics of Traffic Class 2 in [25])[1].

We analytically study the integrated 5G and TSN network in Figure 4 to derive the arrival time of the TSN traffic generated by the sensors to the 5G network ($A_{i,j}$) and the latency requirements that the 5G network must meet (l_i^{5G}). $A_{i,j}$ and l_i^{5G} are estimated by the CNC and transmitted to the 5G network to calculate the radio resource scheduling scheme. Specifically, we use the expressions derived in [27] and shown in (4) and (5). The expression in (4) calculates the time instant at which the first packet of a TSN flow (j=1) arrives at the virtual 5G bridge. This is determined as the sum of the time the packet is generated at the sensor (t_g) and the latency the packet experiences from the moment it is generated until it is received at the DS-TT. The latency components are $l_{sensor} + l_{link_i} + l_{TSN_i} + l_{DS-TT}$, where l_{sensor} is the application processing time at the sensor, l_{TSN_i} is the latency experienced when traversing the TSN bridge, l_{link_i} represents the links between the sensor and the TSN bridge as well as the TSN bridge and the UE, and l_{DS-TT} is the processing time at the DS-TT. In (5), the maximum latency that a packet can experience within the 5G network (l_i^{5G}) is calculated by considering the maximum end-to-end latency l_i^{e2e} minus the time it takes for the packet to travel from the sensor to the 5G network's input port ($A_{i,j}$), and from the NW-TT (which acts as an output port of the 5G virtual bridge) to the PLC ($l_{link_i} + l_{TSN_i} + l_{NW-TT} + l_{PLC}$); being l_{PLC} the application processing time at the PLC, l_{NW-TT} is the processing time at the NW-TT, while l_{link_i}) and l_{TSN_i} are the latency experienced by a TSN flow due to propagation across links and traversing TSN bridges.

$$A_{i,j} = l_{sensor} + l_{link_i} + l_{TSN_i} + l_{DS-TT} \tag{4}$$

$$l_i^{5G} \leq l_i^{e2e} - A_{i,j} - l_{link_i} - l_{TSN_i} - l_{NW-TT} - l_{PLC} \tag{5}$$

In order to calculate $A_{i,j}$ and l_i^{5G} we consider all packets are generated at the same time at the sensors ($t_g = 0$),

[1] Deterministic periodic traffic characterized by the transmission of short packets with strict latency and determinism requirements is typical of industrial applications as indicated in [26].

Table 1
Scenario parameters.

Variable	Value
Work Cell dimensions	10 x 10 m^2
N_F	10-30
$size_i$	40-250 bytes
p_i	4-9 ms
l_i^{e2e}	4 ms
l_{sensor}	3 μs
l_{PLC}	1007 μs
l_{TSN_i}	Calculated following [27]
l_{NW-TT}	0
l_{DS-TT}	5 μs
BW	20 MHz
SCS	30 kHz
MCS	12

and the application processing times at the sensor and PLC (l_{sensor} and l_{PLC}) are given in [28] and [29], respectively. The time required for a flow to traverse a TSN bridge (l_{TSN_i}) is calculated in [27] considering the processing and queuing times at each TSN bridge, which vary according to the traffic load and the transmission time of each TSN flow based on the packet size and the transmission speed of the TSN bridge. Due to short distances between TSN bridges, l_{link_i} is considered negligible. The processing times t_{DS-TT} and t_{NW-TT} are assumed to be 5 μs and 0, respectively, as indicated in [30]. The values considered for each parameter are presented in Table 1.

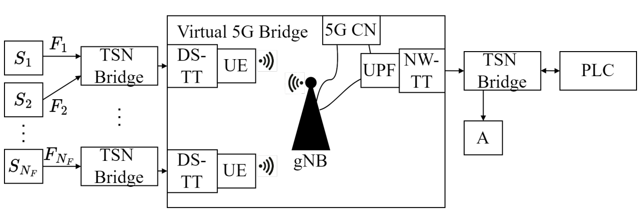

Figure 4: Evaluation scenario.

We simulate a 5G network in Matlab that covers a typical work cell of 10 x 10 m^2. In particular, we consider a private 5G network with a bandwidth of 20 MHz and a SCS equal to 30 kHz, operating in TDD mode following recommendations in [31] for industrial environments. We consider that the UEs are deployed in Line of Sight conditions with the gNB and a fixed MCS value of 12 from Table 1 in [25] is selected for packet transmissions. This choice guarantees an adequate tradeoff between robustness and spectral efficiency[2]. Table 1 summarizes the considered parameters and values.

[2] We evaluated through simulations in 5G-LENA [32] the performance in terms of packet error rate achieved with different MCSs in the configured 5G network. The results demonstrated that MCS12 provides an adequate trade-off between robustness and spectral efficiency.

7. Evaluation

This section compares the performance of the C-FAST proposal against the reference schemes described in Section 5. This analysis has been performed in a computer with an Intel(R) Core (TM) i7-1165G7 CPU @ 2.80GHz and 32GB RAM using Matlab.

7.1. Reliability

Figure 5.a depicts the percentage of satisfactory scheduling solutions as a function of the number of TSN flows (N_F). A solution is satisfactory if all data packets of all TSN flows have radio resources allocated that satisfy their latency requirements and avoid scheduling conflicts. Figure 5.a shows that C-FAST solves an equal number of scheduling problems compared with H-FAST and O-FAST (the number of satisfactory scheduling solutions is slightly higher with O-FAST only when N_F=30 thanks to the use of the optimization techniques). Furthermore, C-FAST obtains solutions for a greater number of scheduling problems compared to commonly used 5G configured grant scheduling schemes (denoted as Ref.). This difference is due to the fact that the resource allocations made with the third reference scheme (Ref.) ensures no overlap in time and frequency for radio resources assigned only for the first packet of each TSN flow. However, the lack of scheduling conflict cannot be guaranteed for the subsequent packets. This can lead to conflicts in the allocation of radio resources to packets transmitted with different periodicities.

Figure 5.b shows the percentage of packets experiencing collisions due to simultaneous assignments for different scheduling schemes. C-FAST, O-FAST, and H-FAST solve the problem of scheduling conflicts but not the reference 5G CG scheduling scheme. For example, with the reference scheme, 13% of the packets experience packet collisions when there are 25 TSN flows, since the reference scheme creates a single CG configuration for each flow. This percentage is considerably high considering that industrial applications may require communications error probabilities below 10^{-7} [25].

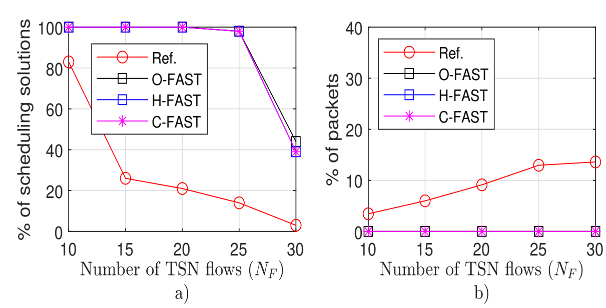

Figure 5: a) Percentage of satisfactory scheduling solutions; b) Percentage of packet collisions.

7.2. Created CG configurations

Table 2 shows the maximum number of CG configurations generated per TSN flow using different scheduling schemes, and the percentage of UEs that are assigned with more than 12 CGs, and hence do not comply with the

Table 2
Created CG configurations as a function of N_F.

	Scheduling Schemes	Number of TSN flows (NF)				
		10	15	20	25	30
Max $CG^i_{c_i}$ assigned to UE	O-FAST	72	72	72	72	72
	H-FAST	72	72	72	72	72
	C-FAST	3	4	5	6	7
% of UEs with c_i >12	O-FAST	26	32	26	30	20
	H-FAST	15	21	20	23	17
	C-FAST	0	0	0	0	0

limit established by 3GPP [8]. Table 2 shows that C-FAST complies with the upper limit of CG configurations imposed by 3GPP in all evaluated scenarios, while the maximum number of CG configurations assigned to UE using O-FAST and H-FAST increases to 72, significantly surpassing the limit (12 CGs).

Figure 6 shows a box plot representing the number of CG configurations created for the UEs when transmitting $N_F = 25$ TSN flows. The red line plot represents the median number of created CGs, while the lower and upper edges of the box correspond to the 25th and 75th percentiles, respectively. The red crosses represent the number of CGs created when it is above the 75th percentile. The black stars represent the upper limit set by 3GPP (12 CGs). Figure 6 shows that the median number of CG configurations created per UE by O-FAST and H-FAST meet the limit established by 3GPP when transmitting $N_F = 25$ TSN flows. However, up to 30% and 23.3% of UEs, respectively, receive more CG configurations than the limit specified in 3GPP standards when using O-FAST and H-FAST. On the other hand, C-FAST complies with this limit for all UEs.

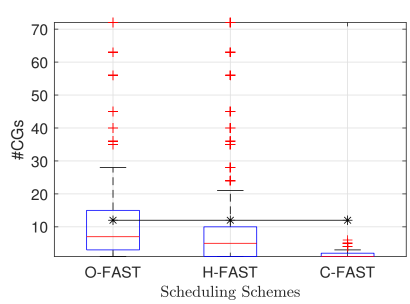

Figure 6: Number of created CG configurations when transmitting N_F=25 TSN flows.

7.3. Latency

Figure 7 compares the average latency experienced by the TSN packets when using the proposed and reference scheduling schemes as a function of the number of TSN flows. The figure also depicts the most restrictive l^{5G} latency requirement. Results in Figure 7 only consider the scheduling problems for which the 5G CG reference scheme achieves a conflict-free solution to ensure a fair comparison between the different scheduling schemes. Figure 7 shows that, although O-FAST and H-FAST result in lower latencies, C-FAST satisfies the latency requirement l^{5G} for all TSN flows. The lower latencies observed with H-FAST are due to the fact that H-FAST employs more CG configurations than C-FAST to avoid scheduling conflicts. O-FAST also achieves lower latency values since O-FAST is based on an optimization problem designed to minimize the latency at the cost of the number of CG configurations (Table 2) and computational time (Section 7.4).

Figure 7 shows that C-FAST and the 5G CG reference scheme achieve the same latency. This outcome was anticipated because if the reference scheme provides a satisfactory solution, then C-FAST will solely utilize a single CG configuration for each TSN flow and will hence experience the same latency as with the reference scheme. However, we should remind that Figure 7 is derived only considering the scheduling problems where the reference scheme achieves a satisfactory solution, and this is achieved for a significantly lower percentage of scheduling problems than C-FAST (Figure 5).

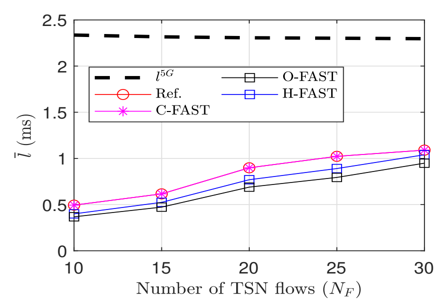

Figure 7: Average latency as a function of N_F flows.

7.4. Computational Time

It is important to highlight that TSN networks can be reconfigured in runtime to enable a faster reconfiguration and facilitate the dynamic inclusion of new devices into the TSN network [2]. In this context, the time required for 5G scheduling schemes to find a solution is crucial for the integration of 5G networks with a runtime reconfigurable TSN network. Figure 8 reports the average computational time necessary for each scheduling scheme to solve the resource allocation problems. The figure shows that the reference scheme presents the lowest computational time while O-FAST exhibits the highest computational time. Figure 8 also shows that C-FAST incurs a slightly higher computational time than H-FAST; however, this time remains low. For instance, in the scenario where 15 TSN flows are transmitted, C-FAST and H-FAST solve the scheduling problem in 37 ms and 30 ms, respectively, while O-FAST needs 309 s. As the number of flows increases, the average computational time also increases. In the case of C-FAST and H-FAST, the average computational time reaches 80 ms and 52 ms, respectively, when 30 TSN flows are transmitted, while O-FAST reaches up to 6h 44 minutes.

The reference scheme achieves the lowest computational time but exhibits significantly lower performance in terms of satisfactorily solving the resource allocation problems. While O-FAST achieves slightly better satisfaction performance than H-FAST and C-FAST (Figure 5) in scenarios with a higher number of TSN flows and lower latency, H-FAST, and C-FAST offer a much better compromise between performance and computational time, in particular as the number of TSN flows increase. C-FAST requires slightly more computational time than H-FAST, although the time remains low [2]. Most importantly, C-FAST requires a lower number of CG configurations and is the scheduling solution that fully complies with 3GPP requirements concerning the maximum number of CG configurations created for each UE. Low computational times will also allow a fast adaptation of the scheduling parameters if needed due for example to changes in the channel conditions experienced by the UEs.

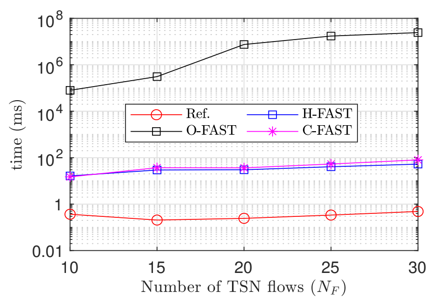

Figure 8: Average computational time (in milliseconds) to allocate radio resources based on different scheduling schemes.

8. Conclusions

This paper has presented and evaluated a new configured grant 5G scheduling scheme C-FAST for an effective integration of 5G and TSN while respecting the 3GPP standard in terms of the maximum number of configured grants per UE possible. C-FAST defines an activation vector that is used by the UEs to activate the CG configurations only when needed, avoiding possible scheduling conflicts between the same radio resource assignment for different UEs or TSN flows. The results demonstrate that C-FAST enables multiple UEs transmitting TSN flows with different periodicities to access radio resources in a coordinated manner reducing scheduling conflicts and improving the reliability of 5G communications supporting TSN. C-FAST offers the best compromise in terms of reliability, latency, computational time, and the required number of CG configurations, and is the only proposal that is compliant with the limitation in terms of the number of CGs per UE established by the 3GPP standard.

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References

[1] 5G-ACIA, *5G for Connected Industries and Automation*, 2019.

[2] M. L. Raagaard, *et al.*, "Runtime reconfiguration of time-sensitive networking (TSN) schedules for Fog Computing," in proc. *IEEE Fog World Congress (FWC)*, Santa Clara, CA, USA, 2017, pp. 1-6.

[3] J. García-Morales, *et al.*, "Latency-Sensitive 5G RAN Slicing for Industry 4.0," in *IEEE Access*, vol. 7, pp. 143139-143159, 2019.

[4] Y. Cai, *et al.*, "Dynamic QoS mapping and adaptive semi-persistent scheduling in 5G-TSN integrated networks," in *China Communications*, vol. 20, no. 4, pp. 340-355, 2023.

[5] M. Yang, *et al.*, "An Uplink Transmission Scheme for TSN Service in 5G Industrial IoT," in proc. *IEEE International Conference on Information and Communication Technology Convergence (ICTC)*, Jeju, Korea (South), 2020, pp. 902-904.

[6] M. C. Lucas-Estañ, *et al.*, "Configured Grant Scheduling for the Support of TSN Traffic in 5G and Beyond Industrial Networks," in proc. *98th IEEE Vehicular Technology Conference (VTC2023-Fall)*, Hong Kong, Hong Kong, 2023, pp. 1-5.

[7] A. Larrañaga, *et al.*, "5G Configured Grant Scheduling for 5G-TSN Integration for the Support of Industry 4.0," in proc. *18th IEEE Wireless On-Demand Network Systems and Services Conference (WONS)*, Madonna di Campiglio, Italy, 2023, pp. 72-79.

[8] 3GPP TSG RAN, "NR and NG-RAN Overall Description; Stage 2," Rel. 17, TS 38.300, v17.5.0, 2023.

[9] IEEE, *IEEE 802.1Q: Standard for Local and Metropolitan Area Networks – Bridges and Bridged Networks*, 2018.

[10] 3GPP TSG RAN, "System Architecture for the 5G System (5GS)," Rel. 17, TS 23.501, v17.3.0, 2023.

[11] 3GPP TSG RAN, "Physical channels and modulation," Rel. 17, TS 38.211, v17.5.0, 2023.

[12] 3GPP TSG RAN, "Medium Access Control (MAC) protocol specification," Rel. 17, TS 38.321, v17.6.0, 2023.

[13] D. Ginthör, *et al.*, "End-to-end Optimized Joint Scheduling of Converged Wireless and Wired Time-Sensitive Networks," in proc. *25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, Vienna, Austria, 2020, pp. 222-229.

[14] D. Ginthor, *et al.*, "Robust End-to-End Schedules for Wireless Time-Sensitive Networks under Correlated Large-scale Fading," in *17th IEEE International Conference on Factory Communication Systems (WFCS)*, Linz, Austria, 2021, pp. 115–122.

[15] X. Wang, *et al.*, "Reinforcement Learning-Based Particle Swarm Optimization for End-to-End Traffic Scheduling in TSN-5G Networks," in *IEEE/ACM Transac. on Networking*, vol. 31, no. 6, pp. 3254-3268, 2023.

[16] J. Yang, *et al.*, "Traffic Scheduling for 5G-TSN Integrated Systems," in proc. *International Symposium on Wireless Communication Systems (ISWCS)*, Hangzhou, China, 2022, pp. 1-6.

[17] D. Ginthör, *et al.*, "5G RAN Slicing for Deterministic Traffic," in proc. *IEEE Wireless Communications and Networking Conference (WCNC)*, Nanjing, China, 2021, pp. 1-6.

[18] D. Krummacker, *et al.*, "Analysis of 5G Channel Access for Collaboration with TSN Concluding at a 5G Scheduling Mechanism," in *Network*, vol. 2, no. 3, pp. 440–455, 2022.

[19] 3GPP TSG RAN WG1 #97, "Enhanced UL configured grant transmissions for URLLC," R1-1906151, Reno, USA, 2019.

[20] 3GPP TSG RAN WG1, "Enhanced UL transmission with configured grant for URLLC," R1-1809165, Gothenburg, Sweden, 2018.
[21] A. Gunturu, *et al.*, "Optimal Configured Grant Selection Method for NR Rel-16 Uplink URLLC," in proc. *IEEE GLOBECOM*,Taipei, Taiwan, 2020, pp. 1-6.
[22] Y. Feng, *et al.*, "Intelligent Radio Resource Allocation for Human-Robot Collaboration," in *IEEE Open Journal of the Communications Society*, vol. 3, pp. 144-158, 2022.
[23] Yungang Pan, *et al.*, "Resource Optimization with 5G Configured Grant Scheduling for Real-Time Applications," in proc. *Design, Automation & Test in Europe Conference & Exhibition (DATE)*, Antwerp, Belgium, 2023, pp. 1-2.
[24] 3GPP TSG RAN, "Physical layer procedures for data," Rel. 18, TS 38.214, v18.0.0, 2023.
[25] K. Montgomery, *et al.*, "Wireless User Requirements for the Factory Workcell," in *NIST Advanced Manufacturing Series*, 300-8, 2019.
[26] 3GPP TSG RAN, "Study on Communication for Automation in Vertical Domains," Rel. 16, TR 22.804, V16.3.0, 2020.
[27] A. Larrañaga, *et al.*, "Analysis of 5G-TSN Integration to Support Industry 4.0," in proc. *25th IEEE ETFA*, Vienna, Austria, 2020, pp. 1111-1114.
[28] MA734 datasheet | 8-Bit to 12.5-Bit, 3μs Low-Latency Contactless Angle Sensor, available at: https://www.monolithicpower.com/en/ma734.html
[29] Rockwell Automation datasheet of 1756 ControlLogix I/O Modules Specifications Technical Data, available at: https://literature.rockwellautomation.com/idc/groups/literature/documents/td/1756-td002_-en-e.pdf
[30] Z. Satka, *et al.*, "Developing a Translation Technique for Converged TSN-5G Communication," in Proc. *18th IEEE International Conference on Factory Communication Systems (WFCS)*, Pavia, Italy, 2022, pp. 1-8.
[31] 3GPP TSG RAN, "Study on physical layer enhancements for NR ultra-reliable and low latency case (URLLC)," Rel. 16, TR 38.824, v16.0.0, 2019.
[32] A. Larrañaga, *et al.*, "An open-source implementation and validation of 5G NR configured grant for URLLC in ns-3 5G LENA: A scheduling case study in industry 4.0 scenarios," in *Journal of Network Computer Applications*, vol. 215, article 103638, 2023.