6G Schedule and Application Traffic Alignment for Efficient Radio Resource Utilization

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***Abstract*—Industry 4.0 promises the increase of productivity and efficiency within manufacturing and industrial processes. A key milestone in this evolution is the 3GPP specification on time-sensitive communication and integration of 5G with time-sensitive networking (TSN), thus enabling the required flexibility for future time-sensitive industrial applications. Although 3GPP introduces ultra-reliable low latency communication (URLLC) features to meet stringent timing requirements, the notable challenge persists in resource overprovisioning, limiting the capacity of the next-generation radio access network (NG-RAN). Our work addresses this by focusing on the sources of packet delay and packet delay variation within the 6G system. Through analysis and proposed enhancements, supported by simulation and measurement results, we aim to minimize queuing delay and optimize 6GS capacity. Our study not only explores standardized 5GS features but also proposes extensions to support periodic deterministic traffic, offering insights to enhance 6GS performance and capacity in real-world scenarios.**

***Index Terms*—5G, 6G, latency, resource utilization, traffic pattern, TSCAI, RAN, scheduling, synchronization**

I. INTRODUCTION

The Industry 4.0 promises on digitization of industrial processes that can significantly improve the productivity, efficiency, and security of the manufacturing industry. The 5G/6G technology enhances flexibility through mobility and support for time-sensitive communication, thereby enabling new innovative industrial use cases. However, this brings in stringent timing and reliability requirements for wireless interfaces, driven by the need for seamless integration with wired networks. In this context, the 3$^{\text{rd}}$ generation partnership project (3GPP) has already specified the integration of the 5G new radio (NR) with IEEE 802.1 time-sensitive networking (TSN) which is crucial for the time-sensitive communication systems and applications [1], [2].

The integration of the 5G/6G with the TSN assumes strict requirements on the end to end (E2E) packet delay (PD), packet delay variation (PDV), and high reliability. Wireless systems inherently exhibit significantly higher PD and PDV compared with the wired systems, due to unpredictable high variations of the wireless channel and the shared medium among many users. This leads to packet loss, retransmissions, and high variations in queuing time, especially in case of time division duplex (TDD) configuration, such as in cellular systems [3]. 3GPP specifies the possibility of fulfilling the stringent timing requirements with the ultra-reliable low-latency communication (URLLC) features [4]. These features are the key enablers for integration of the 6G system (6GS) with the TSN. With URLLC, as specified, it is possible to achieve latency less than 1 ms with the reliability of more than 99,999%.

The main challenge of the URLLC is the resource overprovisioning required to achieve very low guaranteed latency values with very high reliability. It ultimately limits the overall capacity of the 5G system (5GS), as analyzed in [5]. This motivates to focus on the main sources of PD and PDV in the 6GS. A detailed overview of the PD decomposition and contribution of each source of the PD is presented in [6]. From that analysis, it is clear that the main sources of the PD and PDV are: core delay (processing delays), queuing delay (buffered packets waiting for a received grant to transmit) and link delay (consists of segmentation delay, transmission delay and retransmission delay). Moreover, it can be observed that in scenarios where no segmentation and no retransmission occur, a significant PDV arises from the queuing delay. This is directly related to the TDD configuration pattern on one end, and the application traffic arrival time on the other. As aforementioned, overprovisioning of the limited resources on the wireless interface is required in order to achieve low PD and PDV. Therefore, minimizing the PDV would lead to increased capacity of the 6GS in terms of number of users or traffic flows served by the new generation radio access network (NG-RAN).

In this work, we focus on the potential of the 3GPP standardized features for the 5G to lower the PD and PDV by minimizing the aforementioned queuing delay and propose their enhancements to close the identified gaps. In the next section, we define the problem in specific scenarios in more detail and define how the queuing delay can be minimized in an ideal case. In Section III, we explain 3GPP time-sensitive communication (TSC) supporting periodic deterministic traffic and related challenges. In Section IV, we propose possible TSC extensions for external networks such as TSN. In Section V we present the measurement and simulation results of the scenarios where the features, specified by the 3GPP, would help in lowering the PD and PDV, and therefore enabling the improvement of the 6GS capacity.

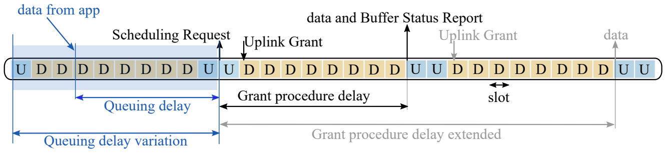


Fig. 1: Delays in a grant-based scheduling approach.

II. PROBLEM DEFINITION ON MISALIGNMENT OF RAN SCHEDULING AND APPLICATION TRAFFIC

The grant-based RAN scheduling, also known as dynamic packet scheduling (DPS), is used by current commercial systems [5]. We explain the uplink (UL) grant-based scheduling procedure through an example as presented in Fig. 1 and Fig. 2. The Queuing delay is among the most significant causes of PDV due to the initial waiting time for an UL slot allocation and its misalignment with the arrival of application data. Fig. 1 and Fig. 2 also present an extended variation of the procedure, highlighted in gray [7]. The extended procedure applies in case when the amount of data to be transmitted is larger that the initial granted resources, e.g., one resource block (RB) is allocated while three are required. In that case, a user equipment (UE) sends the buffer status report (BSR) with the part of data that can fit the initial granted resource, notifies the NG-RAN about the amount of data to be transmitted, and transmits the buffered data in the next granted resource.

As can be seen in Fig. 1, the PD and PDV depend significantly on the TDD pattern, as well as on the slot duration, which depends on the used subcarrier spacing (SCS). E.g., for TDD DL/UL ratio of 8:2 with 30 kHz SCS, the Queuing delay variation is 5 ms. While grant-based scheduling is suitable for the aperiodic traffic, its long handshake procedure of receiving a grant for each packet renders it unsuitable, and non-scalable for the TSC traffic with strict requirements on low PD, even with a TDD pattern of shorter periodicity. On the other hand, a configured grant (CG) based scheduling, with the procedure shown in Fig. 3, is a more suitable option for the periodic traffic. Here, the main sources of the PD and PDV are the processing and the time-alignment of the application's sending times with the scheduled resources. Nevertheless, the main challenge with the CG based approach is the link adaptation (not shown in Fig. 3), where the update of the modulation and coding scheme (MCS) parameters is less frequent and therefore the usage of the shared channel resources is less efficient compared to the grant-based approach.

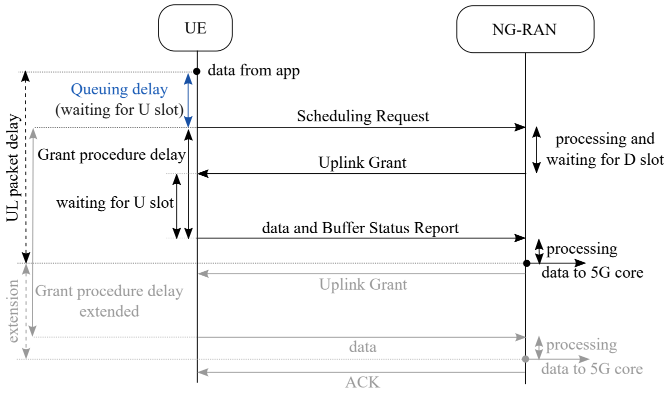


Fig. 2: UL grant-based procedure.

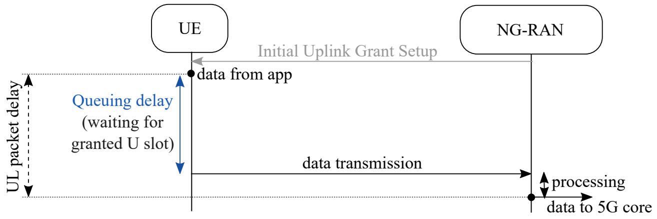


Fig. 3: UL CG-based scheduling.

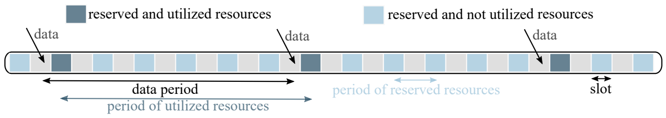
In this work we focus on time-critical applications and therefore only consider CG approach. Moreover, we consider an example of the integration of the TSN with the 6GS. The 6GS is considered as a virtual TSN bridge with certain capabilities and characteristics related to PD and PDV. These capabilities are reported from the 6GS to external networks, in this case to centralized network controller (CNC). TSN end stations are then configured accordingly, such that they comply with the capabilities of all bridges, including the 6G-TSN bridge, as well as adhere with the application requirements that are reported via the centralized user controller (CUC). In this setup, it is important to note that there are two independent central entities, related to the scheduling. One is the CNC, related to the TSN network, and the other is the NG-RAN, related to the scheduling of the wireless interface within the virtual 6G-TSN bridge. This implies that the traffic inside the 6G-TSN bridge waits for arbitrary amount of time to transmit application data since the reserved slot and application data arrival can be misaligned.

In order to further explain the current problem of the alignment of the two aforementioned scheduling, we give a simplified example of a data traffic and the corresponding reserved resources for the radio interface of the NG-RAN on a timeline in Fig. 4. In this simplified scenario, we observe a trade-off between the number of reserved resources and the PDV. In Fig. 4a, it can be seen that the guaranteed maximum PD is lower than the traffic period and it can be fulfilled if there are significantly more reserved resources compared to the amount of the traffic to be transmitted. In this case, low PDV is achieved with overprovisioning of the resources. Examples of realistic use cases with such traffic requirements are summarized in Table I.

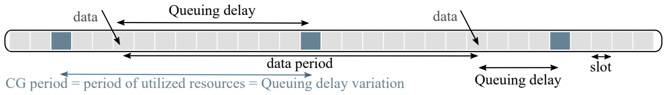
On the other hand, in Fig. 4b, it can be seen that in case of no overprovisioning of the resources, the PDV becomes

TABLE I: 6G use cases with max. PD smaller than the period.

6G use cases [8]	Period (ms)	Max. PD (ms)
Exoskeleton in industrial context		
Motor/Battery status	10	1.5
Tracking user's movement		
Adaptive manufacturing		
Functional safety stop	20	10
Line movement detection	5	2.5
Smart farming		
Monitoring sensors	100	20



(a) Overprovisioning of resources with low PD and PDV.



(b) No overprovisioning, high PDV.

Fig. 4: Trade-off between resource utilization and PDV.

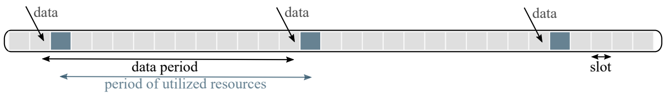


Fig. 5: Ideal use case with time-aligned reserved resources and the data arrival for low PD, low PDV and no overprovisioning.

significantly larger and the maximum PD value is equal to the period of the reserved resources. The distribution of the PD is dependent on the traffic pattern of the incoming data into the 5GS from an external network.

In this work, we do not take into account the PD and PDV contributed by retransmissions. However, it can be reduced either with the cost of resource overprovisioning, or reduced reliability due to a trade-off between the capacity, latency and reliability. For instance, the number of retransmissions is decreased with more robust MCS which reduces the spectral efficiency and therefore the network capacity. Similar is with transmitting the same packet multiple times. On the other hand, reducing the maximum number of retransmissions, or disabling retransmissions completely reduces the latency with the cost of decreased reliability [4]. Other mechanisms to decrease the latency is to use wider SCS, shorter transmission time interval (TTI), or different TDD configurations. However there might be constrains on changing those configuration parameters due to network deployment itself.

Considering the two basic approaches of resource reservation in relation to the incoming traffic data, Fig. 5 presents what would be the ideal case where the low maximum guaranteed PD would be fulfilled without resource overprovisioning. However, in order to achieve this ideal scenario, the pattern of the incoming traffic data into the 6GS needs to be perfectly aligned with the scheduling of the NG-RAN, which is currently unrelated in case of integration of 5GS with external networks, e.g., TSN.

An approach to deal with the explained problem could be estimation of traffic patterns from applications based on the E2E PD measurements for NG-RAN scheduling optimization. From the same measurements, the clock drifts and periodicity mismatches could also be estimated. Although artificial intelligence (AI) models could greatly support in these estimations and optimizations, there would be a scalability challenge. This is because with high amount of quality of service (QoS) flows in the network, it would be challenging to estimate the NG-RAN scheduling for a specific QoS flow of interest, especially because the NG-RAN scheduling changes dynamically. Without a-priori knowing these changes, a significant amount of limited and shared resources on the wireless channel would be occupied for the additional traffic used only for measuring and learning the traffic patterns, based on E2E PD measurements. The previous work [9] tackles the same topic, however not providing comprehensive overview and details of the potential solution. Therefore, in the following sections, we provide a description on how the knowledge of the traffic patterns could be used within the 6GS and externally, e.g., in TSN, in order to align the traffic patterns with the NG-RAN scheduling in a systematic manner to minimize the occupied resources.

III. 3GPP SUPPORT FOR PERIODIC DETERMINISTIC COMMUNICATION

A. *Overview*

In this section, we give an overview of the state-of-the-art of 3GPP standardization regarding support for periodic deterministic communication and transfer of traffic pattern characteristics from/to 5GS to/from external networks, e.g., TSN. The 3GPP, starting from Release 16, describes enablers for TSN TSC, time synchronization and deterministic communication (DetNet), to support periodic deterministic communication [1]. It partly specifies how traffic pattern characteristics known a-priori can be communicated from external networks to the 5GS and among the components within the 5GS. Therefore, TSC assistance information (TSCAI) feature, that describes the TSC flow traffic characteristics at the ingress of the NG-RAN in downlink (DL), and at the egress of the UE in UL direction is seen as an important enabler for the aforementioned problem.

Accurate time synchronization is imperative to ensure coordination among different network elements in order to optimize service performance and reliability. In the case of TDD, accurate network synchronization is inherently needed to ensure time and phase alignment between different NG-RANs, to avoid interference and packet loss. TDD cells functioning on identical or neighboring frequencies within overlapping coverage regions necessitate time domain segregation to avert potential radio frequency interference between base stations and user equipment. This segregation relies on meeting two specific criteria: firstly, ensuring that the cells operate using identical TDD configurations, and secondly, maintaining frame start timing consistency between cells, denoted as the cell phase synchronization accuracy, which should be within a threshold of 3 µs [10]. In the following, we describe details of the TSCAI feature, way of working, current limitations, challenges and possibilities for enhancements.

B. *TSC assistance information and TSC assistance container*

The TSCAI, defined in Table 5.27.2-1 in [1], describes TSC traffic characteristics for use in the 5GS. It may be used by the NG-RAN, if provided by the session management function (SMF). The knowledge of TSC traffic pattern is useful for NG-RAN allowing more efficient scheduling of QoS flows with a periodic, deterministic traffic characteristics either via configured grants, semi-persistent scheduling or with dynamic grants. The flow diagram how the TSC traffic pattern is transferred in a TSC assistance container (TSCAC) from the TSN application function (AF) or TSC time synchronization

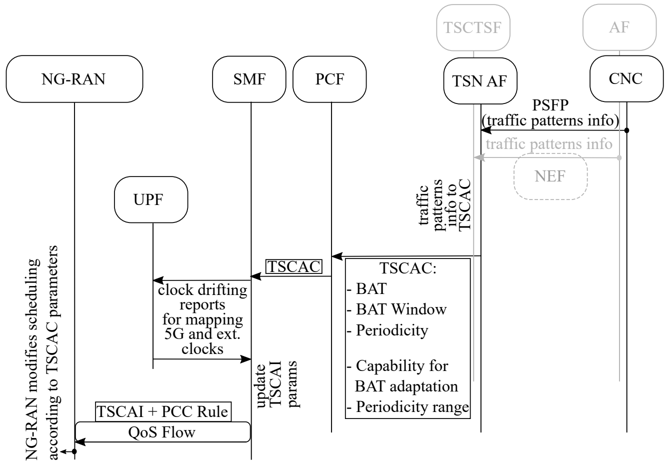


Fig. 6: Flow of the TSCAC within the 5GS towards NG-RAN.

function (TSCTSF), to the SMF where the TSCAI is derived from the TSCAC, and then transferred to the NG-RAN, is presented in Fig. 6. The SMF enables notification control for the QoS flow to receive the *burst arrival time (BAT) offset* along with the “guaranteed flow bit rate (GFBR) can no longer be guaranteed” notification, if the TSCAI contains the *capability for BAT adaptation*.

The determination of TSCAC based on per-stream filtering and policing (PSFP) information applies only to Ethernet type packet data unit (PDU) sessions and only when integrated with TSN. PSFP information may be provided by the CNC if TSN AF has declared PSFP support to CNC. It is important to note here that the means to derive the TSCAC, if PSFP is not supported by 5GS or the CNC, are beyond the scope of 3GPP specifications. In case a TSC service is used instead of TSN, the TSCTSF constructs the TSCAC based on traffic pattern information provided by the AF directly of via network exposure function (NEF), as highlighted in gray color in Fig. 6. The TSN AF or TSCTSF provides the TSCAC to the policy control function (PCF), which forwards it to the SMF as part of policy and charging control (PCC) rule. The SMF binds a PCC rule and the derived TSCAI to a QoS flow and sends it to the NG-RAN. In a special case, UE-UE TSC stream, the (TSN) AF divides the stream into a UL stream and a DL stream, where traffic pattern information is then calculated separately for the two streams. Note that the flow of TSCAI is a 5G control plane feature, although the user plane function (UPF) is involved for the clock drifting reports used at SMF to adapt the external time-based traffic information to the 5G clock.

C. RAN feedback

Fig. 7 shows the flow of NG-RAN feedback parameters determined based on the TSCAI parameters that are received from the SMF for a QoS flow. If the NG-RAN receives the *capability for BAT adaptation* or *BAT window* with the TSCAI, the NG-RAN determines the *BAT offset* parameter. It can reduce the time between the arrival of the traffic bursts and the time of the next possible transmission over the wireless interface. Similarly, if the NG-RAN receives the *periodicity range* with the TSCAI, it determines an *adjusted periodicity*. This parameter should align the period of traffic bursts with the interval of transmission opportunities on the wireless interface.

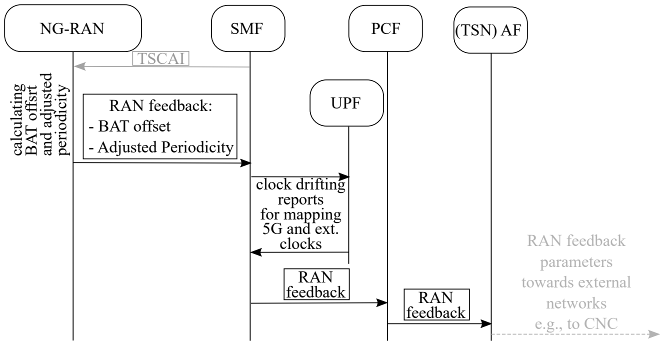


Fig. 7: Flow of the RAN feedback from the NG-RAN.

In case of proactive feedback mechanism, NG-RAN provides the *BAT offset* and *adjusted periodicity* to the SMF in a response to the QoS flow establishment or modification request. In case of reactive RAN feedback mechanism, the NG-RAN may determine that the packet delay budget (PDB) of a QoS flow cannot be fulfilled. Here, it is assumed that the NG-RAN receives the *capability for BAT adaptation* without a *BAT* in the TSCAI and notification control is enabled for a QoS flow. The NG-RAN provides a *BAT offset* to the SMF after the QoS flow establishment when sending the notification “GFBR can no longer be guaranteed”. The NG-RAN shall not provide a *BAT offset* with the same value until the PDB of a QoS flow can be fulfilled. The feedback from the NG-RAN implies that the NG-RAN accepts the *BAT offset*. If the AF-requested *BAT* is acceptable for the NG-RAN, the NG-RAN provides a *BAT offset* of zero and adjust its scheduling accordingly to align with the arriving traffic bursts.

D. Challenges

In [1], specific calculations of the TSCAI parameters are described only in case of integration of the 5GS with the TSN with support of PSFP from both 5GS and the CNC from the TSN side. An additional question is also the precision of the timing parameters, provided and set up based only on PSFP, which is a filtering mechanism to accept incoming/outgoing data bursts in specific time-frames. Means of determining the TSCAI parameters in other cases is out of scope of 3GPP and it has not been discussed so far. Therefore it is an opportunity for the future work of defining the transfer of the TSCAI relevant parameters between external networks and the 6GS.

Another open question is how the *BAT offset* and *adjusted periodicity* can be forwarded from the 6GS, specifically from the (TSN) AF in the 6G core to external networks, such as TSN. Moreover, how the forwarded information can be utilized in external networks to align the traffic coming from the applications at the end stations with the RAN scheduling.

IV. PROPOSED SOLUTIONS FOR THE FLOW OF TRAFFIC PATTERN INFO THROUGH THE 6GS AND TSN NETWORK

A description of the traffic specifications flow from applications via TSN network and how the feedback can be provided back to applications is described in the following.

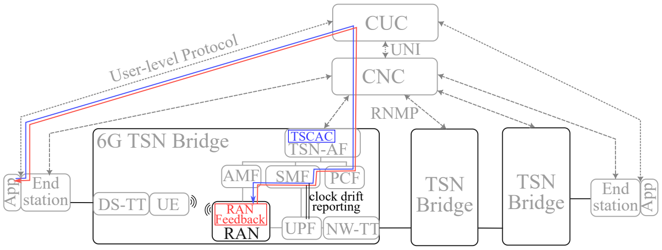


Fig. 8: 6G-TSN integration with the flow of traffic pattern info.

A user defines Traffic Specifications, Network Requirements and Interface Capabilities which includes the configuration that a user is willing to accept from the network [11]. This configuration is related to TSCAI parameters *capability for BAT adaptation* and *periodicity range*. Traffic Specifications include *EarliestTransmit* and *LatestTransmit* from which the TSCAI parameters such as *BAT* and *BAT window* can be calculated. As presented in Fig. 8, the CUC reads these parameters from each end station over a user-level protocol, where different protocols can be used e.g., open platform communications - united architecture (OPC-UA). CUC also designs the streams and selection of Talkers and Listeners and designs the application's timing requirements, e.g., periodic sending times. This defines the interval at which Talkers transmit the data. The parameter *interval* could be used as a TSCAI parameter *periodicity*. CUC then sends the *interval* to end stations using a user-level protocol. Talkers can also use awareness of time synchronization from features of Traffic Specification and Interface Configuration for transmission of frames. An option for a time-aware Talker is to use the enhancements for scheduled traffic, which uses IEEE 802.1AS time to open and close gates of queues (traffic classes) [11]. This describes how the TSCAI relevant parameters can be transferred between the end stations/applications and the CUC.

CNC reads the TSN capabilities of each bridge via a remote network management protocol (RNMP), i.e. NETConf, using YANG data models, and it receives the collected requirements and TSN capabilities of end stations from the CUC via the user-network information (UNI). This describes the transfer of the TSCAI relevant parameters from the CUC to the CNC.

An alternate solution to extract TSCAI parameters is to provide Stream Information, such as *BAT* and *periodicity*, as a service directly from the CNC to the TSN AF, encoded in YANG models [12]. This solution neither requires a new protocol nor the need for PSFP on both 6GS and TSN sides. Moreover, the provided parameters would be with higher precision compared to those extracted from the PSFP parameters. The solution could be generalized where the 6G AF would subscribe for those parameters from an external network which collects these parameters from applications and provides them as a service. This describes the flow of the TSCAI relevant parameters from applications to the TSN AF, while the flow further on towards NG-RAN is already explained in III-B. The complete flow from an application to the NG-RAN is highlighted in Fig. 8 in blue line.

In the other direction, the flow of the RAN feedback from the NG-RAN to the TSN-AF is also described in III-B. As mentioned previously, the currently missing interface for the flow of TSCAI feedback parameters is from the TSN-AF to CNC. A current architectural limitation in the fully centralized TSN configuration is of CNC being central entity that can only send the scheduling configurations but does not receive them back. On the contrary, in case of RAN feedback parameters provided from the TSN AF, the CNC would need to receive the scheduling related instructions/suggestions from the 6G TSN bridge. However, those parameters do not influence the CNC configuration directly, but they should only be forwarded to the CUC. CNC configuration is indirectly affected by receiving the updated Traffic Specification from end stations via CUC in the next iteration, when the CNC might send the modified Interface Configuration to bridges and end stations. Here, an option would be a subscription-based interface, where CNC or even directly CUC would subscribe to the TSN AF service which provides the RAN feedback parameters. Another option would be to add additional parameters to e.g., Interface Capabilities parameters, which are read from each 6G TSN bridge by the CNC via the RNMP.

Further on, assuming the RAN feedback parameters are available at the CNC, they could be forwarded to CUC while returning the Status from the CNC of each stream over the UNI. This includes the success/failure of each Streams configuration and the Interface Configuration for each end station. In case of failure, the CUC might decide to adjust its requirements and try again with updated Traffic Specifications based on the RAN feedback parameters, such as *BAT offset* which could be provided as *offset* parameter and is available in the Status information received from the CNC. The CUC provides the Interface Configuration information for each stream to end stations. An end station can make use of the received information to configure an application in a way that ensures different streams are sent by the application in a specific order that correlates with the expected streams transmission on the network. A CUC can set the initial configuration, manage changes to a running network, or both and it communicates with the end stations using the managed objects [13]. This describes the flow of the RAN feedback parameters from the CNC to the end stations/applications, as highlighted in Fig. 8 in red line.

V. SCENARIOS WITH THE SUPPORT OF TSCAI FEATURE

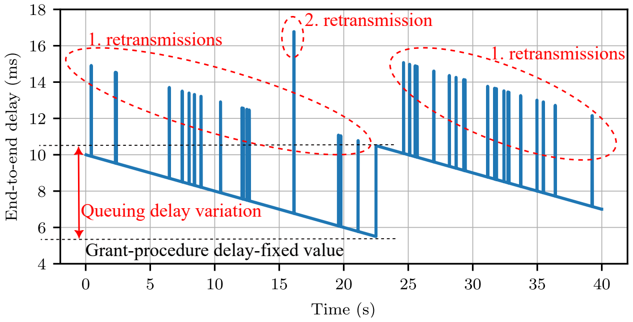
As explained in Section II, the TSCAI feature could save resources on the wireless interface of the 6GS and decrease the PD and PDV in use cases where the traffic pattern characteristics are known a-priori, especially where the traffic coming to the 6GS is periodic. A generic example of a use case where the knowledge of the traffic pattern would be useful is presented in Fig. 4, where the period of the traffic is larger than the required maximum PD and the PDV. There are many defined use cases with such traffic pattern characteristics and delay-related requirements.

The described TSCAI feature and/or RAN feedback are meant to be utilized during the admission control phase on startup of an application, therefore it is assumed that many applications can shift the start of their transmission time and/or periodicity. On the other hand, there could be applications where the time and/or periodicity shift would not be feasible due to strict constraint on synchronization with external systems and other process control loops.

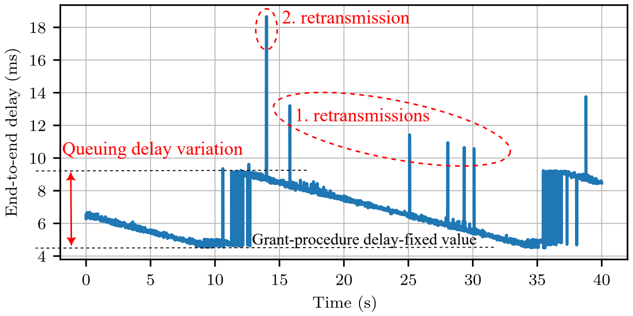
In the grant-based scheduling approach, there are two main delay components: queuing delay and grant procedure delay, as noted in Fig. 1. The first component introduces the most significant PDV, dependent on the traffic arrival time, while the second one introduces the fixed additional delay due to the scheduled request-response procedure. These delay components are presented in Fig. 9, both in the form of simulation and experimental measurements. The OMNET++ platform is used for simulations while the measurements are carried out in an experimental mock factory floor, as described in [14]. OMNET++ simulations and 5G testbed measurements provide the one-way PD in time. Both the simulation and measurement setups configurations have TDD pattern DDDDDDDDUU, 30 kHz SCS, packet size of 50 bytes and sending period of 10 ms. In both setups, the sender and receiver applications are synchronized. However, we introduced an example offset of 200 ppm between the packet sending period and the 5G frame duration to clearly visualize the delay components. In Fig. 9, the Queuing delay and grant-procedure delay components can be seen and connected to the scheduling procedure explained in Fig. 1. We can note that there is a good match between the measurement and simulation results, which verifies that the explained procedure applies to a real-world deployed 5GS. However, as aforementioned, and highlighted in Fig. 9 and Fig. 1, the grant-based scheduling approach introduces an additional PD. It is also not scalable for the deterministic periodic traffic with large number of UEs due to the dynamic scheduling approach which is applied for every sending packet. Therefore, in the following we focus on a CG scheduling approach, suitable for the periodic traffic. As illustration of the CG approach, we modified the simulation setup by removing the fixed delay component originating from the grant-procedure, i.e., the delay from sending the scheduling request (SR) to actual data transmission, as illustrated in Fig. 1 as 'Grant procedure delay'. It is important to note that there is a significant delay contribution from retransmissions, as highlighted in red in Fig. 9, however, as mentioned earlier, this delay contribution is not the focus of this work, and mechanisms to deal with it are mentioned in Section II. In the following subsections, we present several scenarios where the aforementioned TSCAI could be used to decrease the PD and PDV.

A. Fixed time offset between the application traffic bursts and the allocated RAN resources

A simple scenario where the TSCAI information can help is in the case of a fixed time offset between the arrival of the application data and the reserved resources on the wireless interface. This would be the scenario where the 6GS and the external network are perfectly synchronized, e.g., 6GS is acting as a grand master (GM) clock for the external network via the time exposure synchronization functions. Moreover, in this simple scenario it is assumed that the period of traffic burst from applications is the same or a multiple of period of the reserved resources on the wireless interface, scheduled by the NG-RAN. This scenario can be seen in time-domain in Fig. 10. Blue line shows the UL E2E PD in case there is no alignment of the traffic bursts and the NG-RAN scheduling, while orange line shows what could be the scenario if the TSCAI parameters *BAT* and *capability for BAT adaptation* are provided to the 6GS. Either NG-RAN modifies the scheduled resources accordingly or provides the *BAT offset* parameter based on which the application changes its burst sending time. The 1 ms PD in the ideal case represents the propagation and processing delay, modeled with fixed values.



(a) Simulation results.



(b) 5G testbed measurement results.

Fig. 9: Comparison of simulation results with measurements in case of grant-based transmissions.

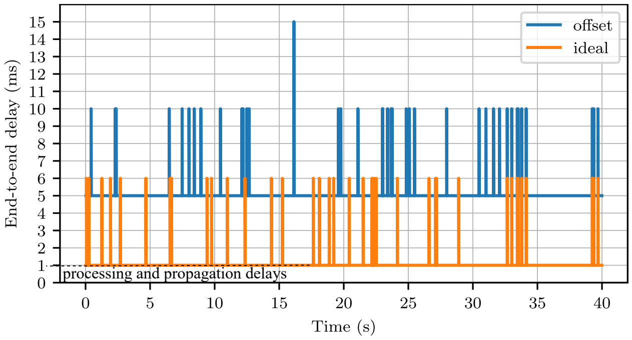


Fig. 10: A scenario with fixed time offset between the traffic data and NG-RAN scheduled resources.

B. Misalignment of the application traffic bursts periodicity and the allocated RAN resources

The second scenario where the TSCAI feature could decrease the PDV is in cases where there is a mismatch between the periodicity of the application data and the reserved resources on the wireless interface. In this scenario, the traffic

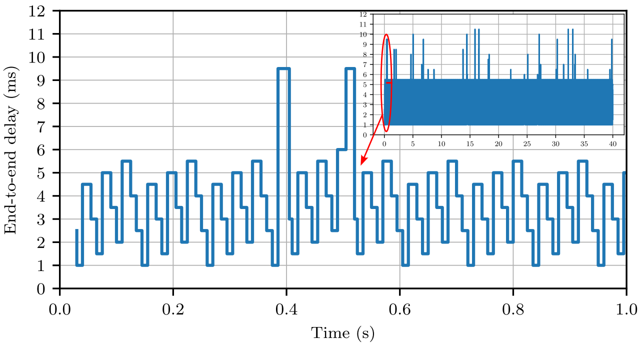


Fig. 11: Scenario with periodicity misalignment between traffic bursts and scheduled resources.

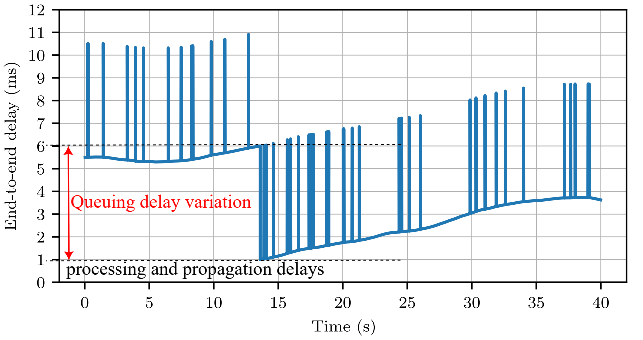


Fig. 12: Clock drift between 6GS and an external network.

is generated with a period of 11.5 ms, while the reserved resources are scheduled with a period of 5 ms. Due to the mismatch of those two periodicities, a significant PDV occurs because different traffic bursts arrive at different slots relative to the start of a frame, while the reserved resources are at fixed slots relative to the start of a frame. Such scenario can be seen in Fig. 11. If the TSCAI feature would be used, and either the NG-RAN align its scheduling based on the *periodicity* parameter, or the application changes its traffic burst period based on the feedback parameter *adjusted periodicity* from the NG-RAN, the alignment can be achieved, resulting in the ideal case, already presented in Fig. 10 (orange line).

C. Clock drift between the 6GS and the external network

The third scenario where the TSCAI can help is if there is a drift or offset between the 6G clock and the clock of an external network, e.g., TSN. The effect of the clock drift would be similar to the periodicity misalignment, explained in previous subsection, however, clock drift results usually in much slower changes of misalignment. In Subsection III-B it is described that SMF, based on the reports from the UPF, compensates the clock drift by modifying the values of relevant TSCAI parameters going to NG-RAN, or the RAN feedback parameters, coming from the NG-RAN. A scenario with the realistic clock drift effect can be seen in Fig. 12, while Fig. 9, previously analyzed, also represents an example of a fixed clock offset. An ideal scenario after the SMF corrections can be seen in Fig. 10 (orange line).

Moreover, the TSCAI feature can compensate also any combination of the presented scenarios, including the traffic offset, periodicity mismatch and clock drift, which is in real-world scenarios the most common.

VI. CONCLUSIONS

In this work, we targeted the queuing PD in cellular communications, originating from a misalignment of the traffic arrival and the availability of the scheduled resources, resulting in significant PDV. We highlighted the importance of standardization support for the periodic deterministic communication in the context of alignment of the traffic sending time with the scheduled resources in the 5G-TSN system. Moreover, we identified the challenges, missing interfaces and proposed enhancements for resource optimization to achieve higher traffic capacity with decreased PD and PDV. We outlined the E2E flow of the TSCAI from applications, via TSN network to the NG-RAN within the 6GS in one direction, and the flow of the RAN feedback in the other direction. Finally, we presented the expected improvements of the PD and PDV, based on measurement and simulation results across various scenarios.

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