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Wireless-aware TSN Engineering: Implications for 5G and Upcoming 6G Networks

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Abstract:

The importance of time- and mission-critical applications is increasing as industries and society are advancing in their digitalization. As such applications introduce stringent quality of service (QoS) requirements on the underlying network infrastructure, open standards like TSN and DetNet are being developed to provide dependable and time-sensitive communication in bridged LAN networks and IP networks, respectively. More recently, the extension to support wireless time-sensitive connectivity has received special interest due to improved network deployment flexibility with mobile devices. These efforts have led to the standardized support of TSN/DetNet in 5G, allowing the 5G system and its mobile devices to be integrated transparently into TSN/DetNet networks while conforming to their user and control plane protocols. Nevertheless, the induced packet delays – and in particular the packet delay variations (PDVs) – of 5G are significantly larger than in their wired counterparts. In this work, we illustrate that established methods to configure TSN/DetNet networks insufficiently address major runtime uncertainties, and that they would consequently result in QoS impairments or scalability issues. We therefore advocate for two systematic approaches to improve traffic shaping in this setting: first, we propose Packet Delay Correction where the PDV is corrected within the 5G system. Second, we introduce "wireless-aware" TSN scheduling to account for the packet delay characteristics of 5G. We demonstrate that wireless-aware TSN scheduling and Packet Delay Correction are complementary in their design and can be combined to provide formal end-to-end reliability guarantees at scale. In addition, being a key aspect to support wireless-aware TSN scheduling in 5G and future 6G networks, we introduce a data-driven framework to predict the packet delay characteristics of the wireless systems over a finite time horizon. Finally, we identify open research questions in wireless-aware TSN engineering and call for action on future studies and standardizations.

1. Introduction

Digital transformation of industries and society is resulting in the emergence of a larger family of time- and/or mission-critical services with needs for high availability. At the same time, these applications present unique requirements distinct from traditional Internet applications like video streaming or web browsing. This general long-term trend of digitalization leads towards a Cyber-Physical Continuum where the monitoring, control, maintenance or augmentation functionality is moved from physical objects to a compute platform with a digital representation, i.e., a digital twin of the object [1]. Communication in this cyber-physical world often includes closed-loop control interactions, which can

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have stringent end-to-end requirements over the entire loop. A dependable time-critical communication is therefore needed to ensure the service requirements.

Over the last decade, several components necessary for such dependable time-critical communication have been developed and standardized; among them are TSN, DetNet, and 5G ultra-reliable and low latency communication (URLLC). While originally initiated from multimedia application requirements, TSN is seen today as an upcoming standardized system of the industrial automation sector to facilitate end-to-end time synchronized communication over Ethernet. Timing granularity and reliability of TSN systems caters to the highest available requirements in industrial automation. In a related fashion, DetNet pursues similar goals but pursues them through layer-3 mechanisms, however, still relying on tight time synchronization and related resource management towards end-to-end guarantees. In a complimentary fashion, 5G URLLC has been standardized to facilitate wireless communication in industrial automation contexts with latencies down to 1 ms and reliability levels up to $1-10^{-6}$. While originally standardized independently of each other, today, first standards are available to integrate the 5G system into TSN and DetNet.

Despite this early progress with standardization, there is more and more realization that the initially standardized systems, and particularly the TSN integration into 5G systems, will not suffice for the convergence and scale anticipated with the future cyber-physical continuum [2]. The design principle of TSN mandates Ethernet time-division multiplexing and router queue management based on tightly synchronized network nodes to facilitate end-to-end latency guarantees. The major invariant of TSN (and in principle also of DetNet) is to achieve these guarantees by assuming individual delay components to be small and deterministic. This relates to transfer times over Ethernet segments or within an Ethernet switch which both have granularities of a few microseconds with marginal variations. This design philosophy is not compatible with typical latencies ranges and variations observed in state-of-the-art wireless systems. Even if considering 5G URLLC systems, wireless latency variations are in the range of hundreds of microseconds. Deployed commercial 5G systems today, i.e., non-URLLC systems have typical latencies in the range of milliseconds and significant stochastic variations due to retransmission recovering occasional random losses. However, the current 5G integration into TSN/DetNet neglects these mismatches, leading essentially to hugely underutilized wireless systems, while still jeopardizing granularities of end-to-end latencies.

In this paper, we present an overview of a set of novel enablers that can address the above challenges. We discuss them in the context of current 5G systems, but since the new features proposed are not available in 5G, they would need to be embraced by an evolution of 5G or upcoming 6G networks. This gives the opportunity to influence both TSN evolution as well as mobile network evolution simultaneously. After giving a summary of the involved systems and state-of-the-art in Section 2, wireless-aware TSN engineering is introduced in Section 3. We then discuss how wireless systems can optimally support these new wireless-aware TSN solutions and point out a few potential opportunities with respect to standardization and future work. Our key insight is that while wireless-aware TSN solutions will allow for more efficient integration, wireless systems will have to become more predictable (but not necessarily more deterministic) to fully utilize our solutions.

2. TSN and 5G Background

IEEE 802.1 TSN and IETF DetNet are networking technologies that can provide E2E dependable time-critical capabilities at layer 2 and layer 3, respectively. TSN (and DetNet) rely on certain traffic shaping mechanisms to achieve these dependable time-critical capabilities. For instance, stringent deterministic guarantees on delay and PDV are typically provided by employing IEEE 802.1Qbv time-aware shaping which works by scheduling time-critical traffic into time slots, based on a precalculated

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schedule, at the egress port of a TSN bridge. These calculations are typically performed within a centralized network controller (CNC), which has a global view on the TSN network and is responsible for configuring the TSN features in both bridges and end-stations. However, they have been specified considering extensions to wired/fixed nodes such as Ethernet bridges and routers.

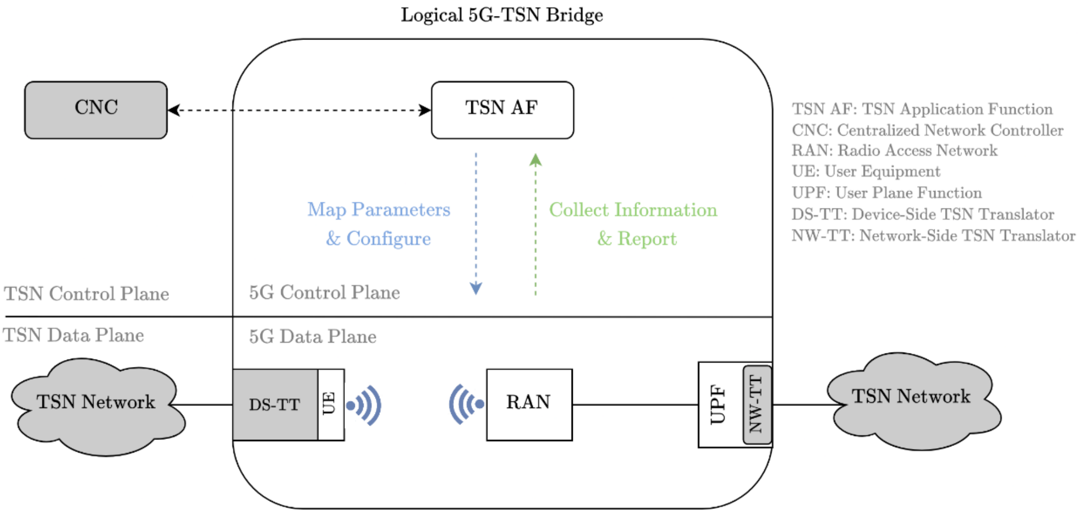

Figure *1*. 5G logical TSN bridge as modeled in 3GPP.

Wireless communication such as 5G came into the picture due to its ease to scale and deploy, as well as its support for mobility that offers great advantages. Support for TSN and DetNet has been standardized in 3GPP through some extensions needed to ensure deterministic functionalities [3] [4]. The most important integration decision relates to the way 5G systems are mapped to TSN/DetNet functional elements: A 5G system – comprising the user equipment (UEs), radio access network (RAN), and core network user plane function (CN UPF) – is modeled as a logical TSN/DetNet node by means of defining translation entities both in the data plane and in the control plane. In other words, a 5G system is integrated as a logical Ethernet switch into TSN/DetNet. As this modeling abstraction is not straightforward, two data plane entities had to be incorporated: the device-side TSN translator (DS-TT), co-located with the device or user equipment (UE), and the network-side TSN translator (NW-TT), co-located at the data-network side at the User-Plane Function (UPF).[1] As shown in *Figure 1*, these two entities implement the interface or port with the external network or next hop. In the control plane, a translation entity interacts with the CNC (for TSN), namely the TSN Application Function (TSN-AF), while for interfacing the DetNet controller a different network function is used, namely the Time-Sensitive Communication and Time Synchronization Function (TSCTSF).

While we focus on TSN in the remainder of this work, our analysis and our proposed solutions can be extended similarly to DetNet. Starting with the analytical considerations, there are significant differences between wired TSN bridges and logical 5G-TSN bridges that have an important impact on scalability and TSN scheduling. We identify the most relevant differences to be related to the typical port-to-port delays and to the coverage area providing a wireless bypass. We discuss both aspects in the following two subsections.

2.1 Port-to-Port Delay Characteristics Affecting TSN Scheduling

Compared to deterministic system models that are commonly employed for wired TSN [8], logical 5G-TSN bridges introduce significant variations in the experienced packet delays. *Figure 2* compares measurements of the port-to-port delay from a TSN bridge (i.e., excluding queueing delay) and the

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[1] In the case of DetNet, only a NW-TT is required.

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corresponding ‘port-to-port' delay of a 5G network deployment [5]. While the TSN bridge can achieve a port-to-port delay of less than 5 microseconds with a packet delay variation (PDV) in the range of 100’s of nanoseconds, the port-to-port delay and PDV of the wireless logical bridge are in the range of milliseconds. A more exhaustive latency analysis for 5G is available in [6]. Cleary, this difference makes an efficient end-to-end integration of 5G and TSN challenging if both wired and wireless network elements are present.

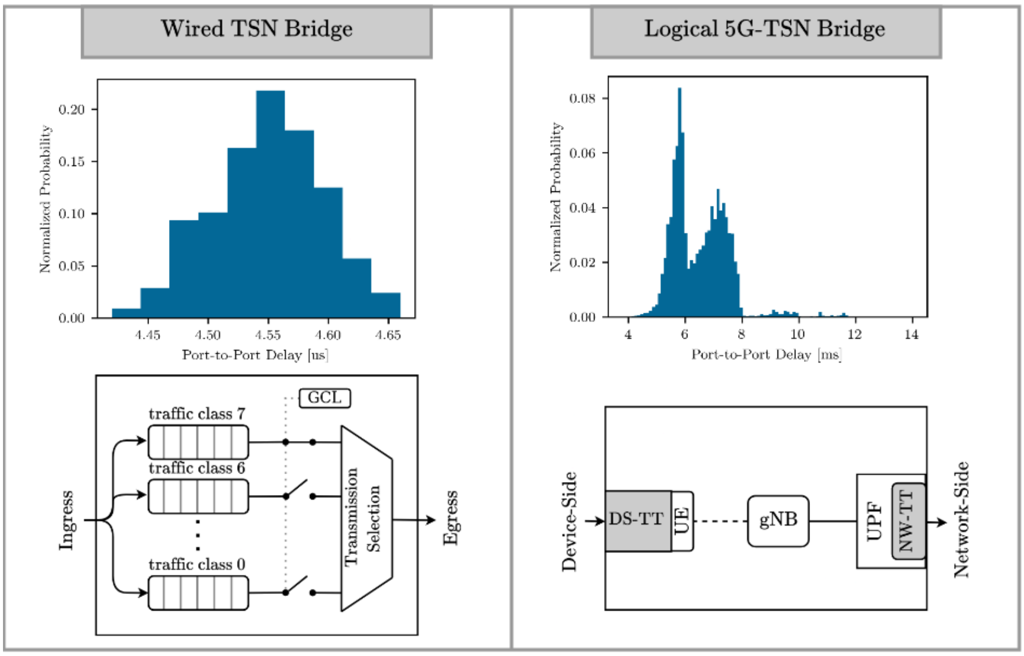

Figure 2: Port-to-port delay of wired TSN bridges vs. wireless 5G-TSN bridges.

To exemplify the effects of port-to-port delays on common TSN traffic scheduling mechanisms, we investigate the behavior of the IEEE 802.1Qbv Time-Aware Shaper in this work as its delay guarantees are directly influenced by port-to-port delays. The Time-Aware Shaper can govern the exact transmission times of frames in each traffic class by introducing a Gate Control List (GCL) to specify the opening and closing time of gates at each egress queue. Hence, the central challenge of providing end-to-end QoS guarantees for each TSN stream is to compute suitable GCLs that are robust against stochastic port-to-port delays as introduced by the logical 5G-TSN bridges.

2.2 Wireless Bypass

While the port-to-port delays of a 5G system are a clear challenge with respect to TSN integration, the wireless medium also opens new opportunities with respect to typical wired TSN deployments. For a wireless 5G-TSN bridge, the distance between ports, i.e., the distance between a UE and UPF, can be up to 100’s of meters or even kilometers. In other words, due to the large coverage of the 5G network, only 1-2 hops (one of which is a wireless node) may be needed from TSN source to destination, while for wired TSN 10’s of hops, and corresponding equipment, might be required to achieve end-to-end connectivity. Therefore, a wireless TSN bridge can be used to substantially simplify the TSN network topology by strategic placement. We call this characteristic the wireless bypass.

A topology with wireless bypass is shown in *Figure 3*. The baseline topology to connect sensors and actuators is a ring topology with multiple wired bridges providing connectivity to controllers executed in an edge cloud environment. This multi-hop ring topology can be simplified substantially using the depicted 5G mobile network providing a single-hop wireless connection to all actuators and sensors in the reach of the wireless network.

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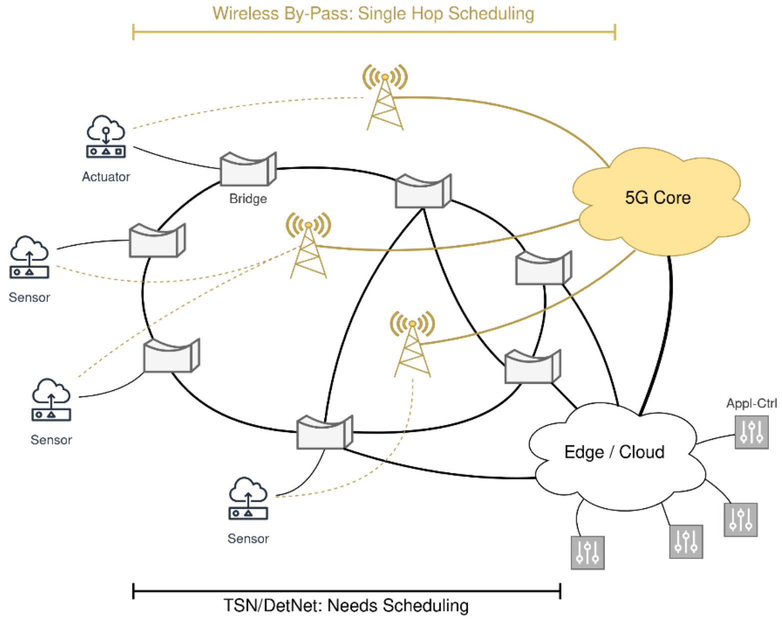

Figure *3*: Wireless bypass.

Due to the wireless bypass, the TSN/DetNet-specific design can be simplified, as congestion scenarios can be solved with proper dimensioning in the radio domain. From this example, it becomes clear that wireless bypass has two major advantages. First, the simplification of the topology can lead to a major reduction in equipment, while logically the reduction of links also potentially simplifies the scheduling and management of congestion (scheduling in TSN is known to be an NP-hard optimization problem). Second, the network capacity can be increased in the system by adding additional radio resources, e.g., densifying radio cells or adding more spectrum carriers, without the need to replace physical interfaces. To sum up, the wireless bypass significantly simplifies the network deployment in all use cases where a legacy wired TSN solution would require a complex network topology and TSN scheduling design.

3. Key Aspects of Wireless-aware TSN engineering

The calculation of IEEE 802.1Qbv [7] schedules for wired TSN networks has received considerable attention (see [8] for an overview of existing approaches). Therefore, it is tempting to re-use these “wireless-unaware” algorithms in networks with wireless bridges. However, this will lead to fundamental challenges as discussed below.

The wireless-unaware algorithms for calculating schedules for wired networks share essential commonalities: time slots are typically assigned exclusively to frames from individual streams at the egress queue of each bridge. The lengths of these time slots include the time required to transmit a frame as well as extra time (called uncertainty interval in the following) to account for the PDV of the port-to-port delay. Thus, wireless-unaware algorithms would conservatively define the uncertainty intervals as the min/max bounds of the port-to-port delay of the bridge, ensuring that frames only use their own time slots to be transmitted exactly in the deterministic order foreseen by the schedule.

The major problem of wireless-unaware Qbv schedules is that exclusive time slot allocation leads to low link utilization, as the min-max 5G packet delay bounds are very large compared to wired bridges (see *Figure 2*). To illustrate, an upper bound on utilization with exclusive time slots can be calculated as the ratio of the actual transmission time (time when link is used for transmission) to slot size

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(transmission time + uncertainty interval). For a wired example, assuming a frame size of 600 B, 100 Mbps link rate (i.e., a transmission time of 48 µs), and 0.26 µs port-to-port delay interval, the maximum link utilization can be estimated as 48 µs / (48 µs + 0.26 µs) = 99%. If we instead assume for a wireless bridge an uncertainty interval of 10 ms, the utilization drops to 0.4%. Moreover, the number of streams that can be safely scheduled decreases drastically (low schedulability) if streams are subject to high uncertainty as shown below in comparison to wireless-aware scheduling.

In contrast, more recent approaches aim to reduce the impact of these conservative bounds. Although deceivingly improving scalability, they often do so in a non-robust way, e.g., choosing the average, median, or maximum packet delay. To illustrate, consider two uplink streams S_1 and S_2 that start their transmission at different DS-TTs at times $5ms$ and $10ms$, respectively. Taking the maximum 5G packet delay of Figure 2 (i.e., $14ms$) does not fully capture the potential delay variation in the range $[3ms, 14ms]$. In particular, it is still possible for S_2 to arrive at the NW-TT earlier than S_1. This form of uncontrolled frame re-ordering can have cascading effects that can even impair the QoS of wired streams; for a formal analysis of such adverse effects, we refer the interested reader to [9]. Most severely, uncontrolled frame re-ordering may even push frame transmissions to the next cycle and far beyond the frame's deadline. Therefore, the question remains: *How can we guarantee reliability with uncertain port-to-port delay of wireless bridges and still have an efficient schedule?* We propose two complementary approaches in the following.

3.1 Packet Delay Correction to Enable Conservative/Classic Scheduling

The underlying idea of Packet Delay Correction (PDC) [6] is to shrink the uncertainty interval by holding back early packets until a predefined minimum residence time in the wireless bridge has passed, before enqueuing them into the egress queue (see *Figure 4*).[2] This effectively folds the left side of the port-to-port-delay distribution to the minimum residence time value. If the minimum residence time is equal to or greater than the maximum value of the original distribution, this leads to a sharp delay peak, i.e., uncertainty is (ideally) eliminated completely. Obviously, artificially holding back frames increases the average delay. So PDC trades off reduced uncertainty (i.e., small PDV) for longer average delay. For the large part of time-critical applications the average latency does not play a role, but rather the certainty that all messages arrive before their maximum delay bound.

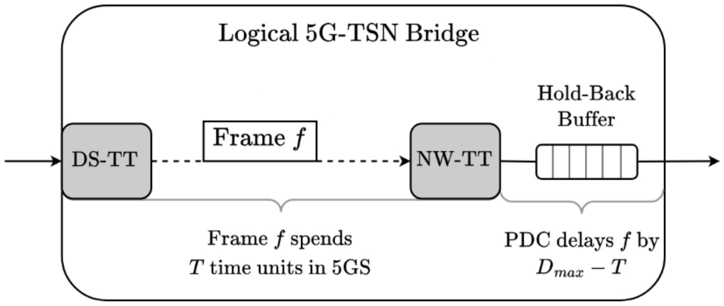

Figure 4: Packet delay correction mechanism.

One way to implement PDC is to timestamp packets at the ingress and implement a hold-back buffer before the egress queue whose release time is controlled by another timer. More specialized approaches are described in [6]. Both the ingress timer and the release timer need to be synchronized, which can be realized using clock synchronization in the 5G system [4] [10].

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[2] Previous discussions about standardizing such functionality in the "hold and forward buffering mechanisms" were held in 3GPP WG SA2 (e.g., 3GPP S2-2002056), but were not standardized and left up to implementation.

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By shrinking the uncertainty interval to a smaller size, in the range of microseconds rather than milliseconds, existing wireless-unaware schedule planning algorithms can be applied without undesired frame re-ordering. However, the degree of delay correction influences the uncertainty interval size and, therefore, the efficiency of the schedule.

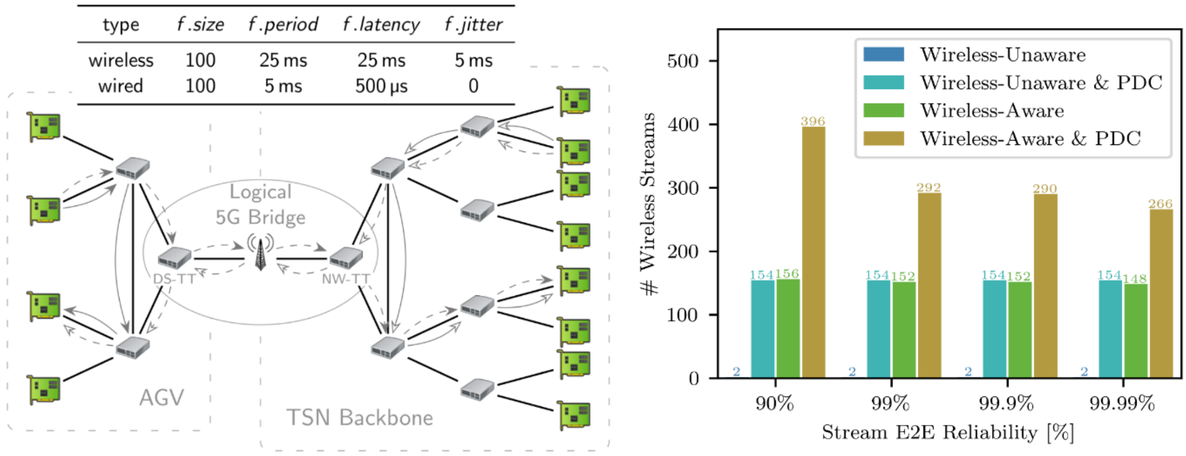
3.2 Robust Wireless-Aware End-to-End Scheduling

As an alternative to the usage of dedicated hold-back buffers, a wireless-aware scheduler can configure the IEEE 802.1Qbv schedule to compensate for a bounded packet delay variation $[d_{min}, d_{max}]$, as perceived in a logical 5G-TSN bridge. It requires that the scheduler (i.e., the CNC) is provided with some statistical knowledge about the 5G packet delays, which can be provided for instance in the form of an empirical histogram. A robust IEEE 802.1Qbv schedule must provide formal end-to-end QoS guarantees for frames whose 5G delays are bounded by $[d_{min}, d_{max}]$. Importantly, these guarantees are made for each individual TSN stream, i.e., transmission faults of one stream must not impair the QoS guarantees of other streams. Moreover, leaving the wireless-aware scheduler to influence the 5G packet delay budgets $[d_{min}, d_{max}]$ has two main advantages:

1. Instead of having to compensate for the maximum PDV, e.g., $[4ms, 14ms]$ for the uplink delays in *Figure 2*, the scheduler can choose a sufficiently large packet delay budget to satisfy the stream's reliability requirement. For instance, a budget of $[4ms, 10ms]$ suffices for streams that solely require a 99% reliability guarantee.
2. In case of a significant disruption in the 5G channel conditions, a wireless-aware scheduler can realize graceful degradation in the streams' latency and reliability guarantees, instead of having to drop individual streams entirely. For example, reducing the 5G packet delay budgets to $[4ms, 9ms]$ may already be enough to find an eligible schedule, while the reliability guarantees are only reduced to 97%.

Striving towards this goal, it is also necessary to address the problem of low schedulability with conventional IEEE 802.1Qbv scheduling approaches. We therefore introduce the concept of controlled frame interleaving: Intuitively, controlled frame interleaving moves away from the conventional approach to exclusively reserve transmission slots for individual frames. Instead, it enables wireless streams to share the same transmission slot by creating frame batches. While allowing frame re-ordering within the same batch to improve link utilization, streams are only allowed to interleave if the streams' latency guarantees can be satisfied (i.e., each frame arrives before its deadline even when being the last one in its batch). For further details, we refer the interested reader to [9].

3.3 Performance Comparison of Wireless-Unaware and Wireless-Aware Scheduling



type	f.size	f.period	f.latency	f.jitter
wireless	100	25 ms	25 ms	5 ms
wired	100	5 ms	500 μs	0

Figure 5: Evaluation setup and results

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Next, we evaluate both presented methods, Packet Delay Correction (PDC) and Wireless-Aware Scheduling, and show that they significantly increase the efficiency of end-to-end scheduling in networks with both wired and wireless network entities. We quantify the efficiency of the considered methods in the number of wireless streams that can be scheduled. To this end, we consider the scenario shown in Figure 5, where an automated guided vehicle (AGV) is connected to the backbone TSN network of a factory. The logical 5G-TSN bridge thus connects two wired TSN network segments: the AGV-internal network (left segment) and the TSN backbone (right segment). All Ethernet links within the wired segments have a data rate of $100Mbps$ and a propagation delay of $50ns$. For packets traversing the logical 5G-TSN bridge, we consider the uplink/downlink 5G packet delay histograms that were obtained in a real 5G system [5]. Moreover, we verify the correct operation of the obtained IEEE 802.1Qbv schedules with our 6GDetCom [11] extension for the OMNeT++/INET framework.

We consider both wired and wireless streams: Wired streams stay within their respective network segments and have stringent latency requirements of $500us$. In contrast, wireless streams traverse the logical 5G-TSN bridge (either in uplink or downlink direction) and have more relaxed latency requirements of $25ms$. Latter latency relaxation is selected as the utilized 5G histograms already have a maximum packet delay of $14ms$ (uplink) and $17ms$ (downlink). Throughout our experiments, we include a fixed number of wired streams (five per wired segment) and try to maximize the number of wireless streams that can be scheduled without violating any stream's QoS requirements. The routes of both wired and wireless streams are randomly chosen. Moreover, we solely consider a single Qbv-governed queue per egress port to amplify the bottleneck of compensating 5G packet delay variations. As time-triggered streams typically have the highest traffic priority, we do not consider any other traffic classes like video, audio, or background traffic.

Figure 5 shows the maximum number of wireless streams for which a feasible IEEE 802.1Qbv schedule is found within 5 minutes of scheduling. The results are shown in dependence of different per-stream reliability requirements (i.e., for each wireless stream, the percentage of frames that satisfy their respective QoS requirements) that range from 90% to 99.99%. First and foremost, the results show the poor scalability of conventional scheduling approaches: Their exclusive slot allocation effectively reserves the egress queue at the NW-TT (DS-TT) for the entirety of the uplink (downlink) min-max 5G packet delay bounds, which only allows room for two wireless streams. This bottleneck is reduced by both our approaches: PDC utilizes dedicated per-stream hold-back buffers that eliminate the need to reserve an egress at the NW-TT (DS-TT). Similarly, Wireless-Aware Scheduling does not rely on exclusive slot reservation and instead allows a controlled interleaving of frames that still upholds the QoS guarantees of each stream. Both approaches, on their own, can already improve scalability by a factor of more than x74. However, the results also show that the best performance is achieved when allowing the Wireless-Aware Scheduler to have control over PDC. Indeed, the scheduler thereby does not necessarily have to use PDC for 100% compensation of the 5G packet delay variations but can fine-tune the compensation for the specific reliability requirement and cut the remaining long-tail (e.g., reducing d_{max} by $4ms$ as in Section 3.2). While this impact fades for ultra-reliability requirements like 99.99% (reducing d_{max} only by $0.7ms$), we find that the batching capability of Wireless-Aware Scheduling allows the scheduler to find a feasible solution faster (before the 5 minute timeout). The results thereby demonstrate that the complementary design of PDC and Wireless-Aware Scheduling also enables the combination of their advantages.

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4. Support of Wireless-aware TSN Engineering in 5G and 6G Networks

As discussed above, one key input to the wireless-aware TSN scheduling is a delay characterization of the underlying wireless system. Given this input, the wireless-aware TSN scheduler determines a Packet Delay Budget (PDB) for each TSN stream. These aspects of wireless-aware TSN scheduling open at least two issues with respect to 5G and future 6G networks: (1) How to determine the delay characterizations serving as input to the wireless-aware scheduling? (2) How to support through wireless scheduling the packet delay budgets, once they are generated?

4.1 5G and Future 6G Performance Characterization

Wireless-aware TSN scheduling, as described above, introduces a certain overhead through its runtime complexity and its system reconfiguration, mandating that the scheduling cannot be executed more frequently than (say) every few minutes. The challenge in performance characterization of the underlying wireless systems is hence to predict PDVs over their future time spans in a confident manner. Data-driven approaches are seen as a key enabler for such performance prediction in future 6G networks, following the broad adoption of AI and ML technologies in 5G and expansion in 6G. Unlike model-driven approaches (e.g., queuing theory and network calculus) for system characterization, data-driven approaches utilize ML methods to identify and learn relationships between system KPIs and other variables from the measurement data [12]. Data-driven approaches have been extensively investigated for network KPI predictions in general. However, characterizing delay in terms of probability distribution is especially useful for end-to-end TSN scheduling [13]. Accurately capturing tail probabilities in delay distributions is critical, as rare but significant delays can greatly impact system dependability for certain applications such as motion control with requirements such as 10 ms delay at 99.999% reliability. Traditional machine learning approaches, such as Mixture Density Networks (MDNs), when combined with Extreme Value Mixture Models, are useful for modeling these tail behaviors, ensuring delay characteristics for these extreme cases are also accurately captured [12]. Additionally, data-driven methods must address the challenge of data drifts, where network conditions and traffic patterns change over time. Adaptive learning techniques are needed to keep predictions accurate and up to date in dynamic environments like 6G systems. Furthermore, there is a need to efficiently expose delay predictions, particularly in how data is represented, i.e., delay histogram or delay range (minimum and maximum delay) and how it is shared with the entities external to 6G system, e.g., CNC [13]. To that end, further extensions and enhancements are required towards life-cycle management of ML models which includes automated ML model training, deployment, monitoring and update.

4.2 5G and Future 6G Performance Optimization

Given the packet delay budgets (PDBs) and reliability levels determined by the wireless-aware scheduler, an obvious requirement in wireless system optimization is to schedule wireless resources according to those metrics. In other words, the RAN scheduler operating at the frame-level must be aware of the PDB and reliability requirements while making scheduling decisions. While wireless resource allocation and link adaptation are ultimately intrinsic functions in 5G and certainly also in future 6G systems, the question of optimal resource allocation opens an important avenue towards support of wireless-aware TSN scheduling. Beyond that, several mechanisms in 5G are already established that can be supportive towards performance optimization. For instance, configured-grant allocation schemes and semi-persistent scheduling are means that significantly contribute to efficient handling of periodic packet streams and reducing corresponding jitter. Owing to the computation complexity of such a scheduling problem, data-driven methods, such as based on RL, can be exploited to arrive at near-optimal schedules [14]. Furthermore, the most relevant contemporary approach to QoS in 5G wireless systems (with respect to time-critical communications) is the implementation of

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URLLC. URLLC enhancements are a key feature of 5G networks introduced in Release 16 designed to meet the stringent requirements of time-critical applications such as RAN delay of 1 ms with 99.999% reliability. To achieve these stringent targets, URLLC employs several enabling technologies. These include short Transmission Time Intervals (TTI), flexible numerology in 5G New Radio (NR), grant-free uplink transmissions and multi-connectivity and diversity techniques. These features, once commercially available, should allow fine-grained wireless scheduling to optimally support PDBs and reliability levels of TSN schedules.

Another set of features that are useful to support TSN over 5G are the 5G QoS framework and TSC assistance information. End-to-end traffic flows are mapped to QoS flows, which receive specific forwarding treatment between the UE and UPF. QoS flows are either set up dynamically or pre-configured. Depending on the availability of stream information in the CNC, the corresponding assistance information can be obtained and used in the QoS flow configuration, which includes parameters such as flow direction, periodicity, and burst arrival time and helps to configure deterministic traffic scheduling in the 5G network. TSN traffic classes are mapped to 5G QoS profiles based on priority and delay requirements. These profiles use the 5G QoS Identifier to define characteristics such as guaranteed bit rate, PDB and packet error rate, ensuring that TSN streams receive the appropriate network resources and treatment through the 5G system. To support efficient integration with TSN, an enhanced QoS framework for 6G could be considered. This may involve introducing new QoS classes or parameters specifically designed for TSN, such as tighter constraints on PDV.

Despite various QoS enhancements, the PDV in 5G TSN bridges remains significantly larger compared to wired TSN bridges. PDC, as already introduced in Section 3.1, can effectively reduce PDV. Depending on the PDC approach, new metadata needs to be transported in the packets traversing the 5G system (e.g., timestamps) or new parameters need to be provided from control plane to the user plane entities of the 5G system. Therefore, efforts in 6G standardization should be towards the specification of the information to be exchanged between 6G NFs and external entities (e.g., CNC) as well as certain protocol modifications will be required to allow appending the relevant metadata in packet headers to implement PDC at the TTs.

End-to-end time synchronization is essential for integrating 6G with TSN, supporting both time-critical applications as well as time-triggered operations like IEEE 802.1 Qbv. 5G already supports gPTP by relaying timing messages and compensates for network delays experienced through the 5G system, while an internal synchronization mechanism is used for timestamping which runs independent of the TSN domain. Beyond the time synchronization support of 5G, for 6G enhancements may be relevant such as a hot-standby setup with primary and secondary grandmasters that aim to enhance time distribution resilience across different configurations [15].

5. Summary: A call for action on future studies and standardizations

The massive adoption of wireless networks makes it attractive to extend TSN/DetNet with wireless communication. This can provide significant benefits in network deployment flexibility and the support of mobile use cases. The 5G standard has adopted support for TSN and DetNet communication over 5G in the standard releases 16-18. To this end, the 5G system behaves within a TSN/DetNet network as a wireless logical node, that adopts the network functionality defined for TSN and DetNet. However, there remains a difference between a wired TSN/DetNet node and a wireless logical TSN/DetNet node in its characteristics. In particular, the delay and packet delay variation of a wireless logical TSN/DetNet node is significantly larger than its wired counterpart.

We have shown for a wireless 5G system integrated into a TSN network, that the large PDV of 5G limits significantly the performance and scalability of the TSN network, when conventional wired approaches to TSN network configuration and traffic management are applied. We have in particular studied the TSN 802.1Qbv mechanism where traffic is time-scheduled through the network. Nevertheless, through novel TSN approaches the performance and scalability can be significantly improved. We have presented two such approaches: one where uncertainties of the wireless system in terms of packet delay variation are removed in the 5G system via packet delay correction. This transforms the 5G system into a system with quasi-deterministic latency characteristics, and it improves the applicability of conventional TSN scheduling mechanisms. A more advanced approach is to enhance the end-to-end scheduling mechanism of TSN such that the packet delay variations of the 5G system are explicitly considered in the TSN scheduling scheme. To this end, it is required to be able to characterize the wireless system delay characteristics, for which we have proposed a data-driven approach. While our solutions are very promising, we acknowledge that many other approaches for optimizing TSN and DetNet communication with wireless 5G networks are possible. As an in-depth analysis of TSN networks and wireless network characteristics are essential for future studies, we have extended the open-source TSN simulator INET with extensions for wireless systems accordingly [11]. We encourage the research community to explore the promising field of wireless-aware TSN engineering.

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