DETERMINISTIC6G

Report on 6G convergence enablers towards deterministic communication standards

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Executive summary

This document provides traffic management concepts for end-to-end deterministic communication based on time-sensitive networking and deterministic networking with 6G wireless nodes. In particular, the differences in packet delay variation between wired and wireless time-sensitive-networking and deterministic-networking nodes, and the impact of the end-to-end performance for different traffic categories, are described. In addition, time-sensitive networking with distributed configuration and the possibility of its integration in heterogenous domains, i.e., with wired and wireless domains, has been explored. Moreover, algorithms to calculate deterministic end-to-end schedules that are robust to high packet delay variation are developed. Also, a more dynamic interaction between bridges and the centralized network controller has been proposed, allowing the control algorithms of the centralized network controller to adapt to end-to-end schedules either reactively based on the dynamic state of the network, e.g., changing latency of network links, or proactively based on the anticipated situation, e.g., when mobile nodes are known to move and need to be handed over between access points.

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1 Introduction

Digital transformation of industries and society is resulting in the emergence of a larger family of time-critical services with needs for high availability and which present unique requirements distinct from traditional Internet applications like video streaming or web browsing. Time-critical services are already known in industrial automation; for example, an industrial control application that might require an End-to-End (E2E) "over the loop" (i.e., from the sensor to the controller back to the actuator) latency of 2 ms and with a communication service requirement of 99.9999% [3GPP16-22261]. But with the increasing digitalization similar requirements are appearing in a growing number of new application domains, such as extended reality, autonomous vehicles and adaptive manufacturing. The general long-term trend of digitalization leads towards a Cyber-Physical Continuum where the monitoring, control and maintenance functionality is moved from physical objects (like a robot, a machine or a tablet device) to a compute platform at some other location, where a digital representation – or digital twin – of the object is operated. Such Cyber Physical System (CPS) applications need a frequent and consistent information exchange between the digital and physical twins. Several technology developments in the Information and Communication Technology (ICT)-sector drive this transition. The proliferation of (edge-) cloud compute paradigms provide new cost-efficient and scalable computing capabilities, that are often more efficient to maintain and evolve compared to embedded compute solutions integrated into the physical objects. It also enables the creation of digital twins as a tool for advanced monitoring, prediction and automation of system components and improved coordination of systems. New techniques based on Machine Learning (ML) can be applied in application design, that can operate over large data sets and profit from scalable compute infrastructure. Offloading compute functionality can also reduce spatial footprint, weight, cost and energy consumption of physical objects, which is in particular important for mobile components, like vehicles, mobile robots, or wearable devices. This approach leads to an increasing need for communication between physical and digital objects, and this communication can span over multiple communication and computational domains. Communication in this cyber-physical world often includes closed-loop control interactions which can have stringent E2E Key Performance Indicator (KPI) (e.g., minimum and maximum Packet Delay (PD)) requirements over the entire loop. In addition, many operations may have high criticality, such as business-critical tasks or even safety relevant operations. Therefore, it is required to provide dependable time-critical communication which provides communication service-assurance to achieve the agreed service requirements.

1.1 DETERMINISTIC6G Approach

Time-critical communication has in the past been mainly prevalent in industrial automation scenarios with special compute hardware like Programmable Logic Controller (PLC), and is based on a wired communication system, such as EtherCat and Powerlink, which is limited to local and isolated network domains which is configured to the specific purpose of the local applications. With the standardization of Time-Sensitive Networking (TSN), and Deterministic Networking (DetNet), similar capabilities are being introduced into the Ethernet and Internet Protocol (IP) networking technologies, which thereby provide a converged multi-service network allowing time-critical applications in a managed network infrastructure allowing for consistent performance with zero packet loss and guaranteed low and bounded latency. The underlying principles are that the network elements (i.e. bridges or routers) and the PLCs can provide a consistent and known performance with negligible stochastic variation, which allows to manage the network configuration to the needs of time-critical applications with known traffic characteristics and requirements.

In fact, several elements in the digitalization journey introduce characteristics that deviate from the assumptions that are considered as baseline in the planning of deterministic networks. There is often an assumption for compute and communication elements, and also applications, that any stochastic behavior can be minimized such that the time characteristics of the element can be clearly associated with tight minimum/maximum bounds. Cloud computing provides efficient scalable compute, but introduces uncertainty in execution times; wireless communications provides flexibility and simplicity, but with inherently stochastic components that lead to Packet Delay Variations (PDV) exceeding significantly those found in wired counterparts; and applications embrace novel technologies (e.g. ML-based or machine-vision-based control) where the traffic characteristics deviate from the strictly deterministic behavior of old-school control. In addition, there will be an increase in dynamic behavior where characteristics of applications, and network or compute elements may change over time in contrast to a static behavior that does not change during runtime. In fact, these deviations of stochastic characteristics make traditional approaches to planning and configuration of E2E time-critical communication networks such as TSN or DetNet, fall short in their performance regarding service performance, scalability and efficiency. Instead, a revolutionary approach to the design, planning and operation of time-critical networks is needed that fully embraces the variability but also dynamic changes that come at the side of introducing wireless connectivity, cloud compute and application innovation. DETERMINISTIC6G has as objective to address these challenges, including the planning of resource allocation for diverse time-critical services E2E over multiple domains, providing efficient resource usage and a scalable solution [SPS+23].

DETERMINISTIC6G takes a novel approach towards converged future infrastructures for scalable CPSs deployment. With respect to networked infrastructures, DETERMINISTIC6G advocates (I) the acceptance and integration of stochastic elements (like wireless links and computational elements) with respect to their stochastic behavior captured through either short-term or longer-term envelopes. Monitoring and prediction of KPIs, for instance latency or reliability, can be leveraged to make individual elements plannable despite a remaining stochastic variance. Nevertheless, system enhancements to mitigate stochastic variances in communication and compute elements are also developed. (II) Next, DETERMINISTIC6G attempts the management of the entire E2E interaction loop (e.g. the control loop) with the underlying stochastic characteristics, especially embracing the integration of compute elements. (III) Finally, due to unavoidable stochastic degradations of individual elements, DETERMINISTIC6G advocates allowing for adaptation between applications running on top such converged and managed network infrastructures. The idea is to introduce flexibility in the application operation such that its requirements can be adjusted at runtime based on prevailing system conditions. This encompasses a larger set of application requirements that (a) can also accept stochastic E2E KPIs, and (b) that possibly can adapt E2E KPI requirements at run-time in harmonization with the networked infrastructure. DETERMINISTIC6G builds on a notion of time-awareness, by ensuring accurate and reliable time synchronicity while also ensuring security-by-design for such dependable time-critical communications. Generally, we extend a notion of deterministic communication (where all behavior of network and compute nodes and applications is pre-determined) towards dependable time-critical communication, where the focus is on ensuring that the communication (and compute) characteristics are managed in order to provide the KPIs and reliability levels that are required by the application. DETERMINISTIC6G facilitates architectures and algorithms for scalable and converged future network infrastructures that enable dependable time-critical communication E2E, across domains and including 6G.

1.2 Introduction to 6G convergence enablers

As aforementioned, one of the objectives of DETERMINISTIC6G project is to address the challenge of stochastic characteristics of wireless connectivity to planning and configuration of E2E time-critical communication networks such as TSN or DetNet over heterogenous domains, which include wired and wireless domains. Therefore, this report provides details on the traffic management concepts for dependable time-critical E2E communication based on TSN and DetNet with 6G wireless nodes and provides insights in on-going research work in 5G/6G to be able to cope with scenarios with more extreme requirements, e.g., sub-ms cycle time. This report also defines three extension directions to overcome the limitations inherited by stochastic wireless systems. In addition, a virtual 5G TSN bridge is compared with the wired TSN bridge in order to understand the main challenges. Moreover, as mentioned in the previous subsection, the DETERMINSTIC6G project aims at a revolutionary approach to the design, planning, and operation of time-critical networks due to inclusion of wireless domains. In particular, in order to address a challenge of stochastic components that lead to PDV significantly beyond what can be found in wired counterparts, in this report, we consider novel algorithms to calculate wireless-friendly E2E schedules that explicitly consider stochastic PD with large PDV along an E2E communication path. By the term 'wireless-friendly', we assume the possibility to capture and efficiently adopt to the fundamentally stochastic and time-variant behavior of wireless systems.

Standards development organizations drive the development of standards and concepts for dependable time-critical communications to ensure delivery of data in reliable and predictable fashion for wired communication systems. IEEE 802.1 TSN has the main role in providing guaranteed high performance connectivity services for certain traffic flows on a common Layer-2 bridged Ethernet infrastructure. Additionally, DetNet, as a deterministic transport solution is being specified by the Internet Engineering Task Force (IETF), ensures bounded latency and low data loss over a Layer-3 routed network. The flexibility of wireless communication motivates also the provisioning of dependable time-critical communication over wireless networks. The 3rd Generation Partnership Project (3GPP) has made significant effort to provide flexibility of wireless communication by enabling 5G System (5GS) interworking with TSN in Releases 16, 17 and 18, as well as interworking with DetNet in Release 18. The 5G support for TSN and DetNet builds on the 5G capabilities for Ultra-Reliable and Low Latency Communication (URLLC) which are included in the 5G standard Releases 15 to 18. TSN / DetNet and 5G complement each other for dependable time-critical communication in wired and wireless domains respectively [SPS+23]. Yet, integration of these technologies is essential for network convergence, i.e., the support for all kinds of communication services via an integrated network infrastructure. Furthermore, interworking and integration of these technologies is needed to support dependable time-critical communication service over heterogeneous infrastructure and multiple application domains required for network convergence. Despite the evolution of TSN, DetNet, and 5G, it is important to note that these standards originate from very different system domains. TSN and DetNet are standards originating from the wired communication domain, in which equipment and components have rather stable and predictable performance characteristics which contrasts with the characteristics of wireless communication. Therefore, the foundation of these different standards is based on fundamentally different ways of capturing and expressing deterministic vs. stochastic characteristics. This leads to significant challenges in the following areas for which this report provides clear problem definitions, concepts, and solutions to overcome those challenges in future networks, i.e., 6G system in combination with TSN and DetNet.

A general problem, addressed in this document, is the fact that even if the 5GS is compatible to the TSN standards as a TSN bridge, there are some substantial differences between a 5GS virtual TSN bridge and a wired TSN bridge. For instance, when a bridge characteristic changes, a new interaction between the bridge and the Centralized Network Controller (CNC) needs to be triggered, which leads to replanning the traffic handling for all TSN streams passing through this bridge which may be quite common for the case of 5G virtual bridges. The replanning of multiple traffic flows by the CNC, may lead to undesirable fluctuations of traffic. A 5GS virtual bridge has some differences in its quantitative characteristics compared to a wired bridge, but also in its scaling behavior, as explained in Section 3.

In this deliverable, the developed traffic management solutions for dependable communications in heterogeneous networks including wired TSN/DetNet nodes and 5G/6G wireless segments, which may act as virtual TSN, DetNet nodes, are described. In particular, the differences in PDV between wired TSN, DetNet nodes and wireless TSN are described, and how DetNet virtual nodes impact the E2E performance for different traffic categories. It is explored if TSN/DetNet traffic management can be improved, by providing richer node characteristics to the CNC beyond the minimum and maximum latency, e.g., by adding percentiles for the expected latency behavior. This information could be exploited by novel algorithms executed by the CNC to calculate E2E schedules for the TSN/DetNet nodes that are robust to delay variation, i.e., beyond the common focus on scalable schedule planning. To this end we propose robustness to delay variation a first-class citizen in schedule planning. Also, a more dynamic interaction between bridges and the CNC is proposed, allowing the control algorithms of the CNC to adapt E2E schedules either reactively based on the dynamic state of the network, e.g., larger changes in latency of network links, or proactively based on the anticipated situations, e.g., when mobile nodes are known to move and need to be handed over between radio cells. The complexity of such dynamic traffic management has been analyzed for possible representation models of the 6G System (6GS). Moreover, the ongoing evolution of TSN and DetNet has been considered, like the introduction of configuration domains for the TSN network, and Reliable and Available Wireless (RAW) extensions for DetNet. A 6G solution for dependable communication shall equally apply for future DetNet solutions as well as for TSN.

Our approach to defining and analyzing 6G capabilities is based on an assessment of 5G. 5G and 5G Advanced have already introduced capabilities to support time-critical communication and have specified functionality to interwork with DetNet and TSN networks. We explore how well these solutions provide a foundation for dependable time-critical communication E2E for future services according to the requirements described in [DET23-D11]. We also identify and propose enhancements to the functionality and capabilities provided by 5G Advanced as standardized until now, in particular to better interwork with TSN and DetNet domains E2E. We call these enhancements as the 6G convergence enablers for dependable time-critical communication. Some of these convergence enablers need to be provided by the 6G system, other enablers may need to be provided by an evolved TSN or DetNet technology. It may be possible to introduce some of these 6G convergence enablers already into 5G Advanced systems. Other 6G enablers may need further maturity or lead to more time in standardization or may not match well with some design decisions defined in the 5G Advanced standards. Those enablers are candidates for consideration in the upcoming 6G standardization. In the context of E2E dependable communication, the interplay across different time-sensitive communication domains, such as TSN, 5G/6G, DetNet is investigated. In this context we denote the 6G system as a “6G DetCom” domain or virtual node within the E2E context.

1.3 Relation to other work packages

The DETERMINISTIC6G project is structured with four technical work packages (WPs). This deliverable belongs to WP3. The features and concepts developed within WP3, partially described in this deliverable will continuously provide an input towards WP1 weaving the E2E architecture for dependable communication. WP2 focuses on the development of 6G centric enablers for ensuring dependable communication services and interacts closely with WP3 that defines the features to enable 6G convergence for dependable communication. The validation of these features is performed in WP4 that provides a feedback by validating the developed concepts.

1.4 Objective of the document

The main objective of this deliverable is twofold: First, the challenges of E2E integrated time-sensitive communication are analysed; and second, wireless-friendly enhancements for TSN and DetNet are designed and developed. The main outputs of the deliverable, related to this objective, are described:

- Reviews the state-of-the-art of TSN (IEEE), DetNet (IETF), TSC (3GPP) and exploration of support of IEEE P802.1Qdd Resource Allocation Protocol (RAP) for integration of TSN with distributed configuration in heterogenous environments, i.e., with wired and wireless domains.
- Explanation on how synchronization, reliability, latency and resource management, as the four major areas of dependable, time-critical communication, can be addressed and covered in 5G/6G network in order to fulfil the strict application requirements.
- Three potential future directions to overcome the limitations inherited by wireless systems are described.
- Comprehensive comparison of a wired and virtual 5G/6G TSN bridge.
- The representation of the DetCom node towards the CNC.
- New algorithms for TSN traffic shaping applied across the E2E dependable communication, considering the difference of wired and wireless DetCom nodes.

1.5 Structure and scope of the document

The document is structured in five sections. The first section serves as an introductory section defining the scope and organization of the document.

Section 2 describes that guaranteed upper bound of service parameters, i.e., bounded low latency, low delay variation, and extremely low loss, can be provided over both (1) Layer-2 bridged and (2) Layer-3 routed network segments. This section focuses on E2E dependable time-critical communication concepts, starting with the description of dependable time-critical communication from the E2E perspective in subsection 2.1. Then, in subsections 2.2, 2.3, 2.4 and 2.5, the state-of-the-art of IEEE 802.1, IEEE P802.1Qdd RAP and its potential support for integration of TSN with distributed configuration in heterogeneous domain, DetNet, and 3GPP standards, are provided, respectively.

Section 3 explains how the four major areas of dependable time-critical communication, that are synchronization, reliability, latency and resource management, can be addressed and covered in 5G/6G network in order to fulfil the strict application requirements. This section focuses on 6G wireless DetCom node, starting with subsection 3.1 with an introduction and overview of the integration of 6G wireless node with wired TSN and DetNet concepts. Subsection 3.2 describes the limitations of the existing specifications/design on E2E dependable communication and provides three

possible future directions to overcome these limitations: (i) to enhance "virtual TSN/DetNet node" characteristics, (ii) to incorporate wireless specifics by the E2E design, (iii) to create a wireless-friendly toolset. Subsection 3.3 compares a virtual 5G TSN bridge with the wired TSN bridge in order to understand the main challenges. Subsection 3.4 describes the criteria for selection of the shaping and scheduling algorithms, while 3.5 focuses on the application of traffic shaping mechanisms on 6G DetCom.

Section 4 focuses on wireless-friendly, adaptive E2E scheduling algorithms, starting with the overview, goals and challenges in current packet scheduling algorithms for real-time systems in subsection 4.1. Then, Subsection 4.2 provides an overview and discussion of the state of the art in real-time E2E packet scheduling. Subsection 4.3 introduces novel approaches and algorithms for wireless-friendly E2E scheduling with a focus on time-driven TSN scheduling as defined in IEEE 802.1Qbv. Subsection 4.4 presents and discusses enhancements to the control plane interface, i.e., how to present network elements towards the network controller.

2 End-to-end deterministic communication concepts

Deterministic communication service provides guaranteed delivery with bounded low latency, low delay variation, and extremely low loss. Extreme values (µsec, lossless, …) of transport requirements often appear in the context of deterministic communication, however the main targets are the guaranteed upper bounds of the service parameters. Deterministic service can be provided over both (1) Layer-2 bridged and (2) Layer-3 routed network segments as well.

Most legacy packet transport services target elastic traffic, i.e., in case of congestion the source can throttle back. In such scenarios the design of the network is around to achieve optimal network utilization, the network throughput is maximized via statistical multiplexing. These legacy networks can provide good average packet latency and the PD probability curves have a long tail. Bounded latency can be achieved by tail drops (resulting in packet loss) or significant over-dimensioning of network resources.

Networks built to provide deterministic service focus on delivery of time-sensitive traffic. The network design is service-centric and optimized to reach service parameters with minimal use of network resources. Zero congestion loss and bounded latency are provided via specific network functions, which if properly configured guarantees that packet delay probability curves are bounded. Mean values of delay do not matter. In-time delivery is ensured by resource allocation.

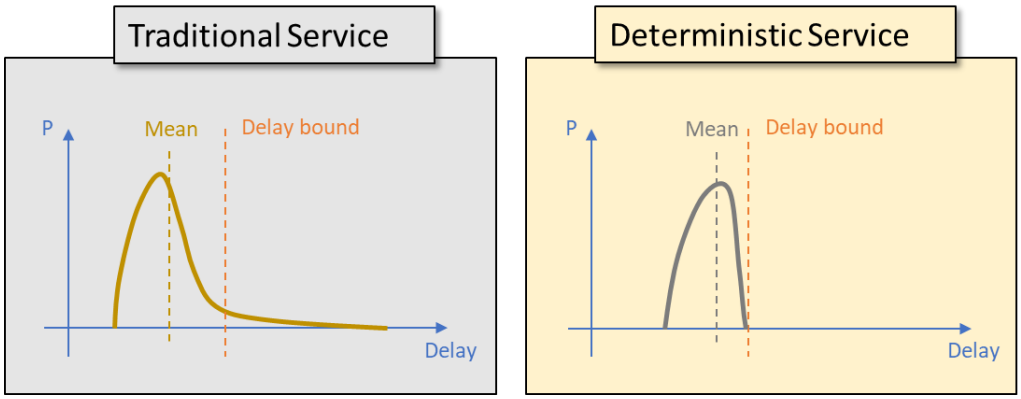


Figure 2.1: Packet Delay Probability for Legacy and Deterministic Networks

So, deterministic data packet delivery can be summarized as “The Right Packet at The Right Time”, i.e., packet delivery over the network happens within a time window without loss or delay due to congestion or errors. In Fig. 2.1, a comparison of the packet delay probability for legacy and deterministic networks is shown.

It is essential to highlight again, that in case of deterministic communication endpoints do not use a traffic control loop, they do not change their generated traffic according to the network characteristics. Endpoints do not throttle back, they simple assume that all generated traffic will be delivered according to the Service Level Agreement (SLA).

There are three major focuses of deterministic network design. First, congestion protection ensures that there is no packet loss due to network congestion. This is achieved by proper queuing and resource reservation, so bounded latency can be guaranteed (note: average delay is not important). Second, service protection designed to achieve outage-less operation despite of link/node failures in the network. Whereas many solutions are used in legacy network to react on failures, it takes time until detour around the failure is established. During this convergence time connectivity is broken and packet loss is expected. For deterministic networks e.g., the per packet replication/elimination was developed in order to ensure service protection without convergence time. It can provide real lossless protection against any type of failures (e.g., random media errors, link/equipment failures). Third, explicit routes (a.k.a. nailed down paths) bypass the impact of the convergence of bridging/routing protocols (i.e., temporary interruptions). Deterministic networks use already defined explicit routing techniques (no new ones are created).

2.1 Overview

This section reviews the state-of-the-art of TSN (IEEE), DetNet (IETF) and TSC (3GPP) standardization. These state-of-the-art standards are built on the acceptance and integration of stochastic elements (like wireless links and computational elements) in the end-to-end deterministic architecture. Design, monitoring and prediction of KPIs, for instance latency or reliability, can be leveraged to make individual elements plannable despite a remaining stochastic variance. This section describes what functionalities were defined in order to address guaranteed upper bound of service parameters, i.e., bounded low latency, low delay variation, and extremely low loss.

In general, the first phase of standardization is finished, what opened the possibility to build interoperable multivendor and multi-technology networks providing deterministic communication services. During the first phase, both IEEE and IETF focused on network scenarios with centralized control, where a central entity ensures proper E2E resource allocation; and IEEE also has distributed protocol-based solutions. State-of-the-art standard 5G can serve many TSN/DetNet scenarios, but not all of them. Deterministic communication scenarios with extreme requirements (e.g., sub-ms cycle time) are out-of-scope for 5G. Standardization and research work is on-going to add further enhanced functionalities to 5G/6G systems in order to being able to cope with more and more extreme scenarios as well.

2.2 State-of-the-art IEEE 802.1 TSN

IEEE 802.1 TSN standards specify the base technology for deterministic behavior in IEEE 802 networks and are continuing to evolve and to address market needs. Furthermore, TSN profile specifications are being developed to ensure interoperability and ease of integration of TSN into various markets, e.g., industrial automation, automotive, and aerospace.

TSN related work extends IEEE 802.1 bridging, TSN is built based on the basics of bridging. TSN components are designed to be add-ons in Ethernet Networks providing a smooth evolution towards multi-service and deterministic networks.

The history of time-sensitive networking started in the IEEE 802.1 AVB Task Group (TG) in 2005. The AVB Task Group (TG) addressed professional audio, video market, consumer electronics and automotive infotainment. However, the resulted AVB standards/features become interesting for other use cases as well, so the scope was extended, and the TG was renamed to IEEE 202.1 TSN TG in 2012.

Fig. 2.2 shows the current state of the TSN TG's work. Several new building blocks/components were defined in four major areas: (1) Time synchronization, (2) Reliability, (3) Latency and (4) Resource reservation. Additionally, the TSN TG defines profiles for the various use-cases, which selects building blocks and their default parameters to be used in those scenarios.

Note: The P802.1DF project (focused on Service Provider profile) expires at the end of this year, and the group decided to abandon it.

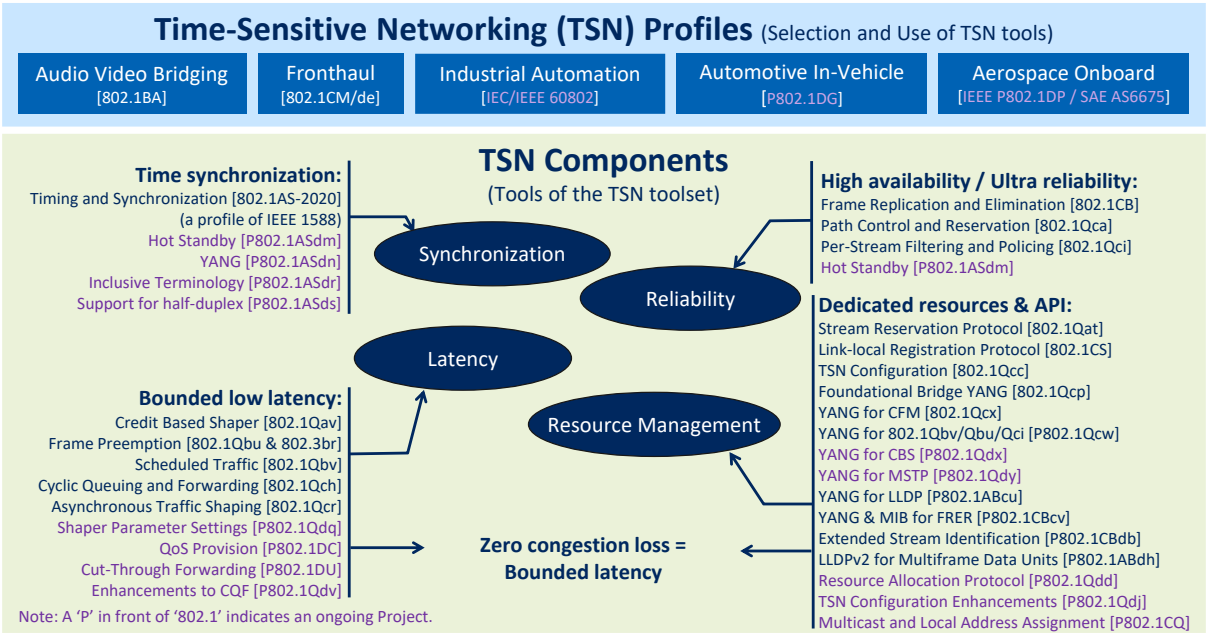


Figure 2.2: Current state of IEEE 802.1 TSN TG work

TSN configuration models and principles are specified by 802.1Qcc. The network obtains requirements from users and configures the bridges to meet user requirements. Various protocols can be used to exchange the configuration information, e.g., remote network management protocols, signaling protocols. The user/network configuration information is specified in a manner that is independent of schema, encoding, or protocol. Three configuration models are defined by 802.1Qcc: (1) fully centralized, (2) fully distributed and (3) centralized network and distributed user. The major focus is on the fully centralized model, as proper setup for most of the components requires detailed knowledge of network resources at each hop. Furthermore, the fully centralized model is a Software Defined Networking Model (SDN) model, which simplifies network devices by having the majority of network control in a Centralized Network Control (CNC) entity. In addition, many use cases, e.g.,

industrial automation include central entity anyways. The fully centralized configuration model is the most mature out of the possible configuration schemes.

An IEEE 802.1 TSN Profile specification selects features, options, defaults, protocols, and procedures. Published IEEE 802.1 TSN profile standards: IEEE Std 802.1BA for AVB networks, IEEE Std 802.1CM TSN for Fronthaul including an amendment on enhancements (IEEE Std 802.1CMde).

Ongoing IEEE 802.1 TSN profile projects are: IEC/IEEE 60802 TSN Profile for Industrial Automation, P802.1DG TSN Profile for Automotive In-Vehicle Ethernet Communications, and P802.1DP / AS6675 TSN Profile for Aerospace onboard Ethernet.

Current (Dec.2023) hot topics are the work on TSN profiles (e.g., IEC/IEEE 60802, P802.1DG), protection for time synchronization (P802.1ASdm), and configuration (e.g., P802.1Qdj, P802.1Qdd, P802.1Qdx, P802.1Qdy, P802.1ASdn) related standards. New projects have been started recently on Cut-Through Forwarding Bridges and Bridged Networks (P802.1DU) and on enhancements to queueing (P802.1Qdv). Furthermore, work is ongoing to make TSN solutions easily available for non-bridge devices (P802.1DC).

Note: all ongoing work can be found here: https://1.ieee802.org/tsn/#Ongoing_TSN_Projects.

2.3 RAP support for dependable time-critical communications

2.3.1 Overview

There are many use-cases and applications which require guaranteed bandwidth and latency requirements. In Ethernet networks, the AVB and TSN standards specify a set of protocols and mechanisms to meet different QoS requirements of various applications. Most of them relate to transmission/queuing functionality and techniques for reservation of resources. Conceptually, ‘reserved streams’ term first appeared in the AVB standards development to guarantee QoS for audio/video streams. The techniques used here assume traffic shaping with the Credit-Based Shaper (CBS) specified in the IEEE Std 802.1Qav-2009 and the SRP specified in the IEEE Std 802.1 Qat-2010 for distributed resource allocation. Driven by the need for guaranteed lowest latency that can be achieved by applying scheduled traffic, the only approach specified so far is with a single CNC for the fully centralized computation (for paths, schedules, and resources), configuration of bridges through remote management, which has been specified in the 802.1Qcc. There, a set of parameters, which are exchanged between end-station and network, carrying the information needed for configuration of the TSN mechanisms are defined. For real-time control systems with very strict low-latency requirements, i.e., lower than hundreds of µs, such as high-speed motion control on the field level, scheduled transmissions with centralized scheduling can minimize the latency to the greatest extent by creating a completely interference-free channel for stream transmissions from talkers to listeners across the network. In such systems, all end-stations must be strictly time-synchronized with the network components to coordinate the transmissions among all the talkers. Moreover, talker schedules need to be aligned with the network schedules. To minimize the latency and jitter, a detailed knowledge of the timing behavior of the network components is required. The CNC needs to know about the requirements and properties of the end-stations where real-time applications are running to calculate the schedules for talkers and network. The configurations are typically managed by an engineering tool.

Nevertheless, a handful of works have put forth approaches for decentralized scheduling in the context of IEEE 802.1Qbv by configuring gate schedules without a CNC [NBT+19][PSP+21]. This has been a motivation of the project to explore the integration of TSN network with decentralized configuration models in a heterogeneous domain, i.e., integration of wires and wireless infrastructure and applications, and to explore the potential changes required within the 6G system to allow this integration.

Besides specific hard real-time systems, there are also many real-time applications having more relaxed latency requirements, usually in the range of milliseconds, e.g., for machine-to-machine communication on the control level. For such applications, a sophisticated scheduling to minimize interference for lowest latency is not necessary. This means not necessarily using the scheduled transmissions relying on a dedicated network controller. However, centralized control with a CNC is so far the only option for configuration of the streams that use the queuing and transmission functions provided by the TSN standards. This is not yet enabled for the distributed scheme. A resource reservation protocol developed to support the TSN QoS functions would enrich the TSN toolset.

The Multiple Stream Registration Protocol (MSRP) propagates registrations for reservation of resources for streams across a bridged network. The initial version, MSRPv0 has been designed to operate according to the fully distributed configuration model. MSRPv1 is an enhancement specified by IEEE Std 802.1Qcc. The MSRPv1 enhancements include support for the centralized network / distributed user model, i.e., MSRPv1 carries stream configuration information between end-stations and their nearest bridges that are edge bridges of a bridged network controlled by a CNC. When MSRPv1 is used in a fully distributed network configuration, it behaves essentially the same as the MSRPv0 with support only for CBS.

Realtime streams have QoS requirements, such as bounded delay, delay variation, and minimum throughput. Bridges can apply specific mechanisms to guarantee the QoS for such streams despite other traffic loads. For instance, the amount of real-time traffic can be limited to avoid network overload. This can be performed per stream or per aggregate with using shapers or policers. On the other hand, scheduled traffic with dedicated transmission slots can be used, also with the admission control. Additional streams are admitted only in case if there is sufficient remaining transmission capacity. Otherwise, admission requests for new streams are declined to protect the already admitted streams.

2.3.2 State-of-the-art RAP

RAP is a hop-by-hop protocol which provides dynamic resource reservation for transmission of time-sensitive streams. The early stage of IEEE P802.1.Qdd Standard draft for local and metropolitan area networks—Bridges and Bridged Networks—Amendment—RAP specifies protocols, procedures, and managed objects for RAP that uses the Link-local Registration Protocol (LRP), as specified in IEEE Std 802.1CS [IEEE23-P802.1Qdd].

The intention of LRP is to transport LRP Data Units (LRPDU) hop-by-hop and to persistently store this data. LRP is similar to IEEE 802.1Q Multiple Registration Protocol (MRP) and it can be used to efficiently distribute bigger databases of up to 1MB between communication peers, which resolves scalability issues of MRP that was optimized for databases of up to 1500 Bytes and adds new proxy mechanisms.

RAP is being prepared by the TSN TG of IEEE 802.1 to allow resource reservation for TSN streams in a distributed fashion, however, a CNC is still needed for network preparation (e.g., create the network design). RAP should provide support for accurate reporting and latency calculation, it can use redundant paths established in combination with other protocols, and is not limited to bridged networks. RAP can be seen as an application running over LRP that supports a larger database with less messages exchanged and thus is economically more feasible than IEEE 802.1Q MSRP built on MRP. Unlike MSRP which specifies only application-specific components within a common architecture, defined by MRP for all MRP applications, RAP is clearly separated in the architecture from the underlying LRP that provides port-local service with data transport and database synchronization functions on a point-to-point link. RAP as a stand-alone protocol specifies a signaling protocol for use in a distributed fashion for streams that intend to use the IEEE 802.1 TSN features defined by IEEE Std 802.1Q and IEEE Std 802.1CB, such as the QoS functions and redundancy. RAP supports Frame Replication and Elimination for Reliability (FRER) as a Seamless Redundancy Technique for E2E, ladder redundancy, and switchover redundancy.

Configuration Domain is a set of stations that are under a common configuration and management scheme, and a single administration. In TSN communication, configuration information exchange is specified independent of scheme, encoding or protocol, as specified in 802.1Qcc. Similarly, configuration information exchange between configuration domains, should also be specified independent of underlying encoding, scheme or protocols. This means that a TSN domain with a certain configuration model (fully centralized, centralized network with distributed user, or fully distributed) is not mandated to implement features of other configuration models in other TSN domains. TSN configuration can conceptually be seen as request/response, as defined by 802.1Qcc, where request means that end station or Centralized User Configuration (CUC) transmits a message which contains a Talker (source of a TSN Stream) or Listener group (destinations of a TSN Stream), while response means that bridge or CNC transmits a message that contains a status group. Here, protocols could be e.g., NETCONF/RESTCONF or signaling, as stated in the individual contribution [FVM+21].

Within a bridge, the RAP-Attribute Propagation (AP) component is responsible for adjusting and propagating the RAP attributes throughout the network. RAP-AP component defines the contexts supported by RAP for attribute propagation, including the Base Spanning Tree Context (by RSTP) and a VLAN context (also with support for redundancy). It also defines the support of seamless redundancy and the rules for:

- adjusting the Talker and Listener attributes before propagating them,
- combing Listener attributes from multiple Listeners toward one associated Talker,
- updating the Dynamic Reservation Entries Stream bandwidth calculations,
- splitting and combining the Talker and Listener attributes, as well as configuring the FRER duplicate filter.

Domain Establishment with RAP

For resource reservation, all devices along the stream path must be in the same RAP domain. A RAP domain comprises the set of neighboring devices with support of RAP and priority for a traffic class. One of eight Resource Allocation classes (RA classes) are characterized by this priority, along with a RA Class Template (RCT). The RCT describes a set of TSN mechanisms which can be applied to streams of a class. Each RAP capable device announces its RA classes link locally to its neighbors to establish a

domain. Devices identify domain boundaries from the priority values of the RA classes. Different traffic shaping mechanisms along a path are possible because the RCT is not evaluated for domain establishment [LSL+21].

An RA class represents a traffic class or a set of traffic classes in a station with a given transmission selection algorithm, in combination with other mechanisms. Moreover, it represents a resource reservation method to provide a bounded latency and zero congestion loss for time-sensitive streams.

RAP end stations exchange structured data, so-called RAP attributes, for resource reservation. There are three attributes defined, encoded as a Type-Length-Value (TLV). Each RAP end station declares RA class attributes for domain establishment.
Talkers send The Talker Announce Attribute (TAA) to their Listeners for conveying stream identification information and traffic specification. For traffic specification, specifically for token bucket-based shaping, RAP offers a TLV, which includes minimum/maximum frame size, committed information rate, and burst size. An alternative is the MSRP traffic specification, which includes maximum number of frame sizes and frames per interval. In addition, the network uses the TAA to compute the worst-case latency of a path and inform about the status to the Listener.
Listeners declare The Listener Attach Attribute (LAA) for communicating the interest in participating in a stream. The network uses it to perform admission control status to the Talker. The status in the LAAs can be Listener Ready, Failed, or Partial Failed. All attributes can be extended by adding custom features to RAP.

Resource Reservation Process

A control application of an end station initiates a resource reservation process with RAP requiring QoS guarantees for its application data streams. Following, Talkers declare TAAs and Listeners declare LAAs to request resources for streams from the network.

Each Talker declares a TAA which propagates via bridges in the direction of all Listeners along the stream path. On receipt of a TAA, bridges evaluate if sufficient resources are available for the requested stream. If resources are available, the attribute is forwarded in the direction of the Listeners. Otherwise, failure information is attached to the TAA before forwarding. For computation of the path latency in the worst case, bridges add their maximum forwarding latency to the accumulated latency field in the TAA. Each Listener declares a LAA to inform about the participation in a stream. After a TAA and LAA of the same stream are registered on bridge ports, resources for the stream are reserved, and related QoS mechanisms are configured. When a bridge receives multiple LAAs for the same stream, it combines the status information of all received LAAs before forwarding to the Talker. After resources are successfully reserved, the control application which initiated resource reservation is notified by RAP that it can start deterministic data transmission.

Latency, bandwidth and resource constraint

One of the parameters contains the upper bound on the latency for a given RA class and a given port is treated as a latency guarantee provided by the bridge to each stream that has been reserved for transmission in that RA class and through that port. If RAP determines that allowing a new stream transmission would cause a stream transmission in one or more RA classes on the bridge to suffer from a latency higher than the corresponding *maxHopLatency* value, it denies a stream request to ensure a latency upper bound for each stream that is already reserved on the bridge. If RAP determines that the total bandwidth needed to transmit that stream and all the streams already reserved in the same RA class and on the same port has exceeded the amount indicated in the corresponding *maxBandwidth* value, it denies a stream request. If it determines that the bridge does not have sufficient resources available for supporting all the operations required for handling that stream, it denies a stream request.

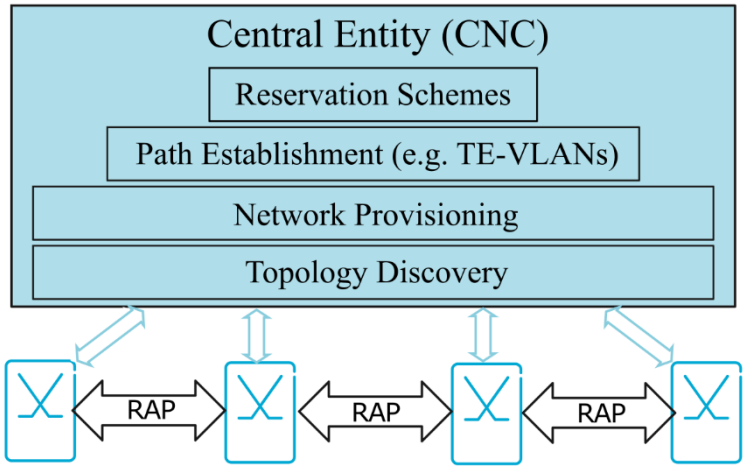


Figure 2.3: Centralized network configuration with distributed reservation using RAP [Far21]

In the following, a summary of RAP for distributed stream configuration will be listed. First, each IEEE 802.1 queuing/transmission selection can be combined with distributed SR for isochronous control loops with guaranteed low latency, reservation combined with TAS, reservation combined with CQF (Cyclic Queuing and Forwarding), etc. Second, stream transmission over redundant paths (e.g., 802.1CB FRER) can be combined with distributed stream reservation. Moreover, combining proxying capabilities with distributed stream reservation allows support for: centralized components (CUC/CNC) and constrained devices. In the case RAP is used in industrial automation, there is still a central entity (CNC), as it is clearly shown in [D21]. Even though the Central Entity is not called CNC in the previous reference, there is CNC as it implements functions of a CNC as per IEEE Std 802.1Qcc-2018. In use cases, other than industrial automation, a fully distributed model, without central entity, can be used with RAP [Far21].

Referring to Fig. 2.3, actual resource reservation (resource allocation) is performed by a distributed protocol (RAP/LRP), but a Central Entity (CNC in TSN terms) is involved in the preparation of the network to make the distributed reservation possible for certain traffic, e.g., topology discovery, domains configuration, preparation of forwarding paths (active topologies), VLANs, reservation schemes, synchronization, etc. RAP operates on VLAN context span by Multicast VLAN Registration Protocol (MVRP) or Central Entity. Central Entity configures e.g., RA Classes, and establishes reservation schemes for certain mechanisms, e.g., for Scheduled Traffic (IEEE 802.1Qbv).

Challenges

Conclusions from the individual contribution [Far21] to RAP are summarized in the following.
First, the "single point of failure" argument is invalid as both fully centralized network model and 'centralized model with distributed reservation' (hybrid) approaches include a central entity, even in case of the RAP approach when used for industrial automation. Note that a fully distributed model, without central entity could be possible for other use-cases, where the required performance, e.g., PD and PDV, is more relaxed. Then, bridges are a lot simpler in case of the fully centralized configuration whereas each bridge must implement RAP and LRP for distributed reservation (on top of the features needed for centralized configuration). There is a central entity in both configuration models (CNC as per IEEE 802.1Qcc). The central entity is involved in the same operations to some extent in both cases. The central entity in the case of RAP provides the paths (e.g., VLAN) and the basis for reservation for Streams, which are traffic engineered in case of industrial automation. The central entity in the fully centralized case goes beyond by performing the reservations as well. The difference is not significant as the central entity is capable of it anyhow. Many more optimizations, including global optimizations, are possible in the case of the fully centralized model. All, including Plug & Produce and dynamic addition and removal of streams are provided by the fully centralized configuration, which is more capable overall with simpler devices. Moreover, the major challenge for dependable communication, e.g., in industrial automation use-cases, is the knowledge of all the sources, destinations and the full overview of the network from the E2E perspective. With the current definition of RAP, this information is not shared and available across the entire network, but only among the neighbors. Only the central entity has this information, even in the case where RAP is used for the resource reservation. The usage of RAP would be beneficial if a central entity is not needed, however, there are still too many open questions on how the RAP should work, to fulfil all the requirements, especially related to latency and reliability, in a fully distributed network configuration.

Since RAP amendment is still in early stage, further enhancements of the protocol are expected and it will guide us on its utility and potential support for E2E communication in networks with distributed configuration model. A current challenge, which might be addressed in the future with further developments, is whether RAP will support the inter-TSN domain configuration and subsequently address the scalability issue of multi-domain TSN networks.

A potential future work is to explore RAP integration with non-centralized configuration in heterogeneous domain, i.e., including the wired and wireless domains. Moreover, further discussions are needed on how 6G architecture should evolve for RAP integration to support distributed configuration.

2.4 State-of-the-art DetNet

DetNet operates at the IP or Multi Protocol Label Switching (MPLS) layer and is for networks that are under a single administrative control or within a closed group of administrative control. So, DetNet is not used for large groups of domains such as the Internet. DetNet service provides a capability for the delivery of data flows with (1) extremely low packet loss rates and/or (2) bounded E2E delivery latency. DetNet defines common architecture with IEEE 802.1 TSN, and there is close collaboration between the two groups. The DetNet Working Group (WG) has been formed in 2015.

Note1: These characteristics are accomplished by dedicating network resources such as link bandwidth and buffer space to DetNet flows and/or classes of DetNet flows, and by protecting packets during forwarding across the DetNet network (e.g., by replicating them along multiple paths).

Note2: Unused reserved resources are available to non-DetNet flows as long as all guarantees are fulfilled.

Building blocks/components of DetNet architecture are similar to the ones for TSN (i.e., (1) Time synchronization, (2) Reliability, (3) Latency and (4) Resource reservation). However, the DetNet WG does not deal with synchronization. DetNet WG leverages various time-synchronization techniques and profiles that are defined elsewhere to address the needs of different market segments.

DetNet functionalities are implemented in two adjacent sub-layers in the protocol stack: the service sub-layer and the forwarding sublayer (see Fig. 2.4).

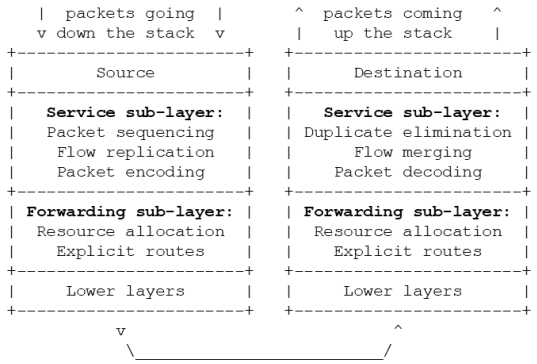


Figure 2.4: DetNet sub-layers

Service protection addresses random media errors and equipment failures e.g., packet replication and elimination (against failures), packet encoding (against media errors), re-ordering (ensure in-order delivery). In the forwarding sub-layer resource allocation ensures resources along the path of a DetNet flow, e.g., buffer space or link bandwidth, and addresses two of the DetNet QoS requirements, namely latency and packet loss. Explicit routes address the impact of convergence of routing or bridging protocols (i.e., temporary interruptions of forwarding).

As per writing this document (Dec. 2023) the DetNet WG has already finished the “First release” of standards. They use existing technologies (e.g., traffic engineering, pseudo-wire technology), there is no new IP header field defined in data plane (it is rather built on specific use of existing ones) and for configuration the fully centralized approach (i.e., Software Defined Networking controller (SDNc)) is proposed. Topics covered by the first standards package are: problem statement, use cases, architecture, two data planes (IP, MPLS), security, flow information model and YANG [RFC 7950] model.

The list of DetNet RFCs can be reviewed here: https://datatracker.ietf.org/wg/detnet/documents/.

Recent results of the WG are related to Operations, Administration, and Maintenance (OAM) and data plane refinements (i.e., integrating replication and elimination in the IP data plane (PREOF) and defining packet ordering algorithms). Work is in progress on the controller plane framework, scalability requirements and new queueing techniques to provide deterministic latency.

Wireless extensions to DetNet were provided by a dedicated WG, the RAW WG. DetNet solutions apply to both wireless and wired networks, but wireless medium presents significant challenges to achieve deterministic properties such as low packet error rate, bounded consecutive losses, and bounded latency. RAW WG focused on wireless extensions of DetNet and covered various medias, e.g., IEEE Std. 802.15.4 Time-Slotted Channel Hopping (TSCH), 3GPP 5G URLLC, IEEE 802.11ax/be and L-band Digital Aeronautical Communications System (LDACS).

During summer of 2023 the RAW WG was integrated into the DetNet WG.

2.5 State-of-the-art 3GPP

Fig. 2.5 shows the evolution of deterministic communication capabilities in 3GPP releases. This section does not provide a comprehensive description/analysis of various 3GPP releases and assumes that the reader is aware of 3GPP system architectures. After a general overview, more details are provided about the scope and results of the latest 3GPP release (Rel-18).

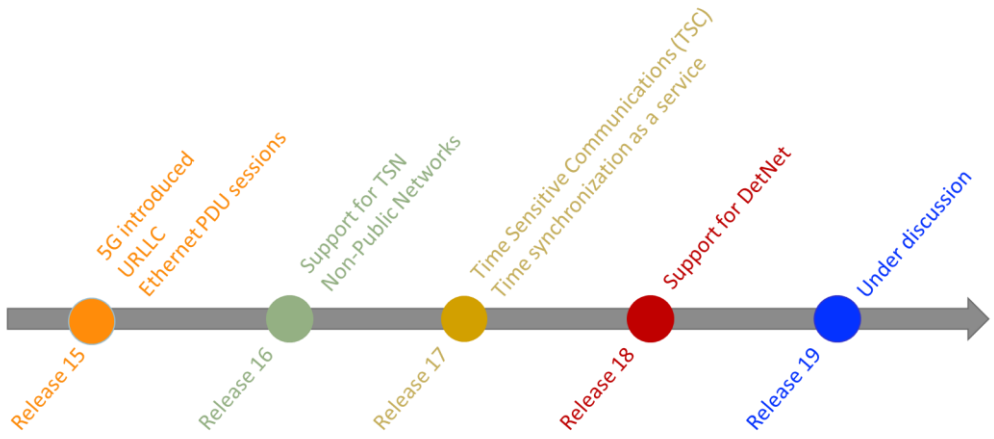


Figure 2.5: Deterministic communication capabilities in 3GPP releases

The basic concept to support deterministic communication scenarios by 3GPP systems is to model the 5GS as a “virtual TSN/DetNet node”. The node granularity is on a per User Plane Function (UPF) basis (at the 5G core network), and the UE interface is defined using the Time Sensitive Communication (TSC) framework.

From a data plane perspective, it is essential to support TSN stream / DetNet flow identification. A stream/flow is associated to a QoS flow in 5GS which is identified based on policy rules in the UPF or in the UE. QoS configurations are based on the existing 3GPP QoS model and there are no implications identified for the Radio Access Network (RAN). However, additional assistance information is provided also to RAN, including the flow direction, periodicity, burst arrival time, and survival time.

From a control plane viewpoint, interaction with a TSN/DetNet controller must be ensured. Such an interface is used to report information towards the TSN/DetNet controller and to receive configuration for the 5GS. Additionally, a mapping of the YANG model into meaningful 5GS parameters should be performed. These functions can be performed by the Time Sensitive Communications and Time Synchronization Function (TSCTSF) for DetNet and in the TSN Application Function (AF) for TSN in the 5G control plane, by adding the necessary extensions.

TSN/DetNet requires the capability to explicitly set the bridging/routing on a per flow basis by the external controller(s). There are 3GPP defined mechanisms for setting the routing and the 3GPP specification also allows the UPF to perform bridging, but the 3GPP specifications do not fully comply with IETF and IEEE requirements. In general bridging/routing service is out-of-scope for 3GPP specifications, therefore in real network scenarios bridging and routing are for example implemented by additional (external) functions located mainly within or next to the UPF. Note that support for multicast mechanisms in 3GPP are very limited and insufficient for TSN/DetNet purposes on its own.

5G interworking with TSN has been specified in particular in Release 16 and 17. The 5G-TSN interworking is documented in [3GPP23-23501], and also in [5GA-TSN21], [FVM+19] [GRL+20] [5GS20-D51] [5GS20-D52] [5GA-TSN21]. Section 3 and 4 provide an overview of 5G-TSN integration. In Release-18 3GPP SA2 WG has focused on 5GS DetNet interworking. The corresponding work item or normative work for Release 18 started in January 2023. The study has discussed two Key Issues (KI) according to 3GPP TR 23.700-46. The first KI is about 5GS DetNet node reporting, which includes studying: (i) which information the 5GS needs to report; (ii) how the 5GS collects the information to report; and (iii) clarification on whether the Network Exposure Function (NEF) could be deployed between the TSCTSF and the DetNet controller. The second KI is about provisioning DetNet configuration from the DetNet controller to 5GS, which includes studying: (i) which parameters provided by the DetNet controller should be mapped into which 5G parameters, (ii) how the 5GS finds the Packet Data Unit (PDU) Sessions corresponding to the given DetNet configuration, and, (iii) what mechanisms are used in 5GS to configure the system according to the configuration provided by the DetNet controller. The agreed architecture is shown in Fig. 2.6.

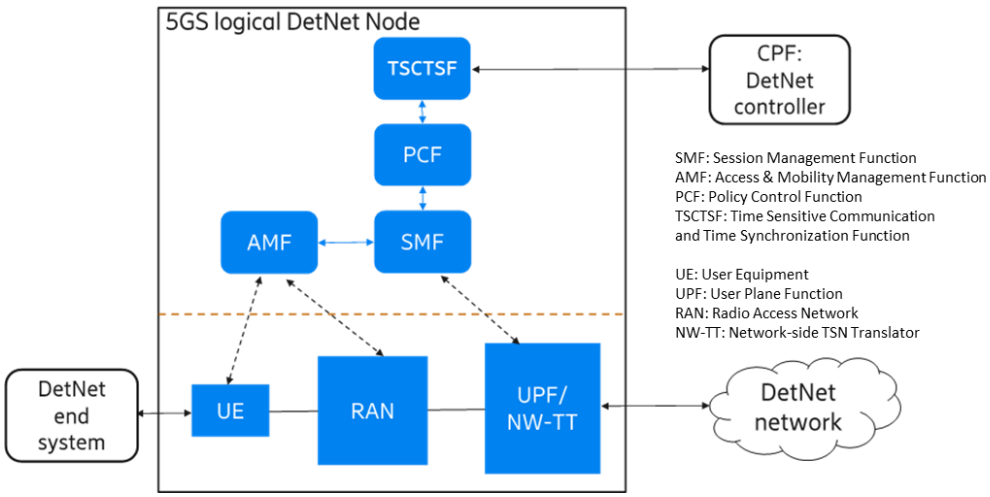


Figure 2.6: Architecture for 5GS interworking with DetNet (Rel-18)

Like for TSN and TSC, integration of DetNet in 5G considers the 5GS as a logical DetNet node with a per-UPF granularity. Each node and interface are identified by a node ID and an interface ID, respectively. Interfaces correspond to PDU sessions and to Network-side interfaces. TSCTSF terminates the interface with the DetNet controller. YANG models are exchanged using existing configuration protocols such as Netconf or Restconf.

The 5GS by means of the TSCTSF exposes or reports information towards the DetNet controller. The reporting information is collected by TSCTSF from the Session Management Function (SMF) and the UPF and its Network-Side TSC Translator (NW-TT), as per existing procedures TSC in Release 17.

Note: in case of DetNet there is no mandatory TT on the device side (DS-TT). The DS-TT is optional and depends on the need of functions (e.g., for providing time synchronization) in a given network scenario.

Work in 3GPP has been completed in the normative phase of the work item. No signaling mechanism to include the NEF in the path between TSCTSF and the DetNet controller has been standardized by 3GPP. If NEF functionality is desired, the relevant functions such as the authentication, authorization, and potential throttling of signaling can be achieved by including such functionality in the TSCTSF depending on the needs of the given deployment. A YANG extension that allows the DetNet controller to explicitly provide (5GS) DetNet node traffic requirements may be used and is being specified in 3GPP based on IETF feedback.

Limitations in current standards resulted partly from the scoping of the 3GPP work as it was agreed for example that UE impacts or 5GS routing impacts are out of scope of Release 18, and partly from the fact that the 3GPP architecture does not fully support general IP routers on the UE side. As noted above adding external bridging/routing functionalities can hide these missing standards, but requires creative system integration solutions and will result in de-facto best practices in real network scenarios.

Note: 3GPP systems do not support the MPLS data plane of DetNet due to the lack of support for MPLS. TSN scenarios are supported by the Ethernet PDU session and DetNet IP data plane is supported via the IP PDU session.

3 6G wireless DetCom

Flexibility and mobility are great advantages provided by 3GPP networks, however integration of 5G/6G in networks with deterministic capabilities has its specific challenges. In order to fulfil the strict requirements of deterministic applications all the four major areas of deterministic communication (see Fig. 2.2, Synchronization, Reliability, Latency and Resource Management) have to be addressed and covered in 5G/6G segments.

First, synchronization must be provided over the air interface in use cases where the endpoints and/or network functions require E2E synchronization. Second, resiliency and interaction with reliability network functions outside of the 5G/6G domain must be ensured. Third, for bounded latency a careful configuration of the 5G/6G system is important with differentiated traffic handling for different traffic flows and aligned with the new traffic shaping methods defined for TSN and DetNet. Finally, resource management must be addressed to expose 6G network specific resource parameters and support their communication with external managed entities (e.g., CNC, Software-Defined Networking controller (SDNc) for DetNet).

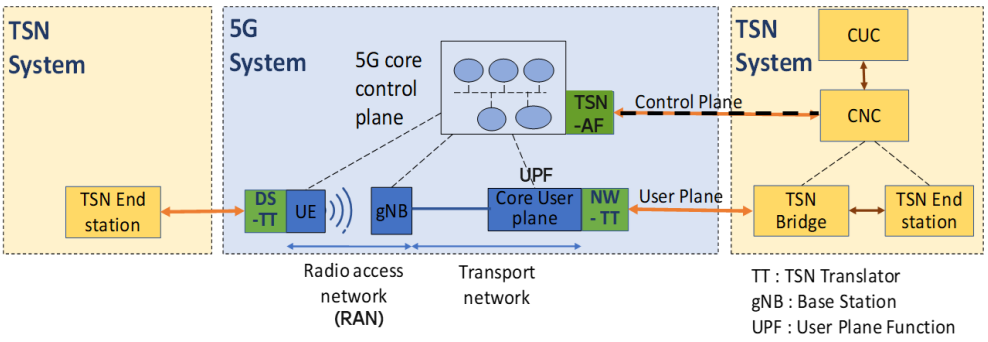


Figure 3.1: 3GPP Rel-16: 5G TSN support (User Plane and Control Plane)

To meet deterministic requirements, 3GPP standards have defined two data plane entities to incorporate deterministic functionalities: DS-TT and NW-TT (see Fig. 3.1). Furthermore, support for TSN has been added by introducing a TSN Application Function (TSN-AF) as control-plane entity to interface the 5GS with the TSN Controller CNC, as described in [FVM+19] [GRL+20] [5GS20-D51] [5GS20-D52] [5GA-TSN21] [3GPP23-23501] and shown in Fig. 3.1. TSN-AF functionality has been generalized as a TSCTSF for control/management plane communication and exposure of 5G/6G capabilities/parameters for DetNet and other TSC services. While delivering TSN and DetNet is in principle supported by 5G, there remain several details in practical operation that need further validation (especially for scenarios with extreme requirements). Also, the efficiency of 5G at scale - when connected to a larger TSN network - needs to be further investigated.

It was found that these deviations of stochastic characteristics make traditional approaches to planning and configuration of E2E time-critical communication networks such as TSN or DetNet, fall short in their performance regarding service performance, scalability and efficiency. Therefore, this section defines three extension directions to overcome the limitations inherited by wireless systems. In addition, a virtual 5G TSN bridge is compared with the wired TSN bridge in order to understand the main challenges.

3.1 Overview

Original TSN work in IEEE 802.1 was started with the assumption, that the network is built using point-to-point wired links. Of course, the need for wireless extension to allow mobility in deterministic communication raised early, but initially most components were designed without considering wireless specifics. Wireless related discussions were more about how to adapt wireless segments to the meanwhile defined deterministic building blocks.

There are two possible choices on how to treat the wireless segment in the E2E network architecture: (1) the whole wireless system is treated as a point-to-point link or (2) as a virtual deterministic node (bridge/router). Due to the radio technology inherited characteristics the implementation of functions required for the first option would result in extreme and hard-to-implement system components, therefore all standardization efforts were focused on the second option.

The major challenge for a wireless system to act like a virtual deterministic node is that a wireless system (and its external interfaces) is by nature distributed and with dynamic variations due to radio propagation. The radio transmission suffers from interferences, reflections, scattering and diffraction that affect the reliability of data communications which results in high variable forwarding latency,

see a deeper review in [DET23-D21]. Wireless systems cannot behave like a wired node having non-blocking, zero loss and (almost) zero-delay backplane between its local interfaces. Wired nodes have a switching backplane with single digit microsecond processing delay and practically zero delay variation (see Section 4.3.4).

Furthermore, a virtual deterministic node must be equipped with components regarding all the four pillars (synchronization, resiliency, bounded latency, resource management). 3GPP work (Rel-15/16/17/18) has focused on all of them. URLLC features targeted reliability, latency and QoS (e.g., automatic repetitions, antenna techniques, robust physical channels, Orthogonal Frequency Division Multiplex (OFDM) numerology, mini-slots, grant-free access, pre-emption, 5G QoS identifier (5QI) values for multiple time-critical services, QoS monitoring). Providing synchronization and exposure functionality were covered as well.

Some of the functionalities are loosely specified, like the “Hold and Forward” buffers in 23.501 that aims to support scheduled traffic (an intended equivalent of IEEE 802.1Qbv). 3GPP does not specify how the Hold and Forward buffers should be implemented.

Additionally, one new challenge can be identified in 3GPP regarding deterministic communication. In the context of bounded latency, there are no results regarding how to incorporate the impact of the wireless system specific PD and PDV characteristics (i.e., they have a much wider value range than the typical values of wired nodes) on the E2E design of deterministic communication (see design specific details in section 4.).

3.2 Limitations of the existing specifications/design on E2E deterministic communication

Current state-of-the-art is that the early deterministic wireless standardization intended to build as much as possible on existing functionalities/architectures, therefore it has focused on scenarios, where the wireless system behaves like a “virtual TSN bridge” (i.e., trying to emulate the operation and characteristics of a wired TSN bridge). Due to the fundamental differences of multi-endpoint radio links and point-to-point wired links, such a “virtual node” will unavoidably differ in characteristics. The algorithms that are investigated for TSN make assumptions that differ from those 5G-TSN characteristics, and a review of algorithms is needed that provide efficient performance for TSN E2E with 5G-TSN nodes.

There are three extension directions listed below to overcome the limitations inherited by wireless systems, especially 3GPP ones:

1. Enhance “virtual TSN/DetNet node” characteristics.
2. Incorporate wireless specifics by the E2E design.
3. Create a wireless-friendly toolset.

Direction-1: Enhance “virtual TSN/DetNet node” characteristics. This direction mitigates the characteristics difference of the “virtual node” and focuses on solutions to fix the wireless specific characteristic (e.g., compensate packet delay variation before a frame/packet leaves the wireless domain). This direction focuses exclusively on the wireless domain and its internal functionalities.

Examples: (1) packet delay compensation using the number of radio retransmission. (2) packet delay correction using ingress timestamps/slots.

Note: this direction is covered in WP2 (see DETERMINISTIC6G deliverable D2.1 [DET23-D21]).

Direction-2: Incorporate wireless specifics. This direction improves the existing E2E deterministic communication design/tools to tolerate wireless specifics (e.g., algorithms that can work with a wide range of parameters (like significantly different of min/max port-to-port delay)). This direction focuses on building blocks that can be used E2E (i.e., at any point of the TSN architecture). One of the directions that is explored (e.g., in IETF for DetNet) may require extra meta-data to travel with the packet (e.g., the number of already used waiting time or cycles during forwarding) and may need additional network wide functionality (e.g., frequency synchronization).

Examples that are being investigated and may be relevant are: (1) urgency-based forwarding (2) modified CQF stages/design (nodes can have variable/multiple cycles).

Direction-3: Being wireless-friendly. This direction evolves the deterministic toolset with (possibly new) building blocks that have wireless-friendly characteristics. Wireless-friendly means that stochastic behavior of wireless technologies is considered during the creation of these building blocks. Examples that can be explored are e.g., timestamp-based queuing algorithm, or a simplified E2E architecture, that takes advantage of the limited hop-count that is a typical side-effect of using wireless connectivity. Also, this direction might benefit from extra metadata to travel within the packet (e.g., timestamp) and might need additional network-wide functionality (e.g., phase synchronization).

Examples: (1) ingress timestamping and forwarding at each hop based on the timestamp. (2) Single hop network design with over-dimensioned aggregation links towards centralized virtual endpoints in the cloud.

Note: Adding wireless segments to deterministic networks are not the only hot topic for building such networks. Further deliverable (i.e., D3.3) of this project will cover scenarios where the addition of wireless segments is combined with cloudification of the deterministic application. The main rationale of that is that 5G/6G architecture integrates cloud technologies as a common platform to be used.

3.3 Comparison between a wired TSN bridge and a 5G virtual TSN bridge

The way how 5G has specified the interworking with TSN is to specify the 5GS as a virtual TSN bridge. We want to review the commonalities and differences between these two types of bridges, which are shown in Fig. 3.2.

A wired TSN bridge is shown in Fig. 3.2 (a). Ethernet traffic enters the bridge at an ingress port, passes through the bridge and leaves the bridge at an egress port. Ingress traffic is forwarded to the corresponding egress port via the bridging fabric depending on the traffic destination. Different Ethernet traffic, including TSN streams, can be categorized into traffic classes and served by up to 8 egress queues at each egress port. The bridge also has a management interface that interacts with the TSN controller for bridge capability reporting and configuration. IEEE 802.1 does not specify the detailed realization of the TSN bridge, this is left to the implementation choice of bridge vendors. What IEEE 802.1 specifies are traffic handling mechanisms. For example, it can be defined how traffic shall be processed per traffic class or TSN stream for e.g., policing and filtering (as specified in e.g., IEEE802.1Qci). It can also be specified how the traffic shaping at the egress ports shall be performed, which means how traffic from the (up to eight) different queues for the different traffic classes shall be scheduled onto the egress Ethernet link. In addition, it is specified how the bridge needs to support

time synchronization via gPTP (i.e., Generalized Precision Time Protocol IEEE802.1AS). Further, the interaction of the TSN bridge with the TSN controller, the CNC, specifies how the bridge is configured for different TSN features, and how the TSN bridge reports its capabilities to the CNC for TSN planning purposes.

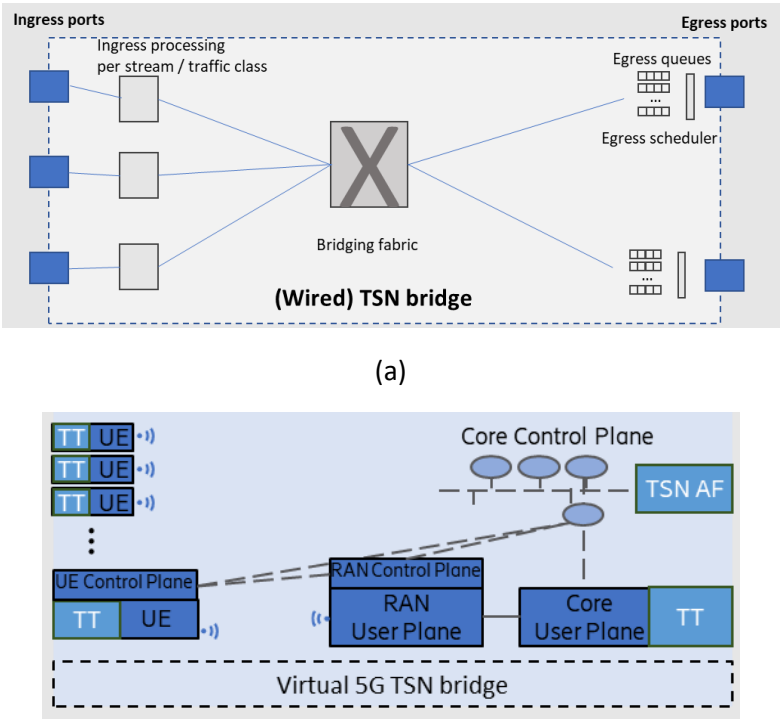


Figure 3.2: Comparison of a wired TSN bridge (a) and a virtual 5G TSN bridge (b)

A virtual 5G TSN bridge is shown in Fig. 3.2 (b). Ethernet traffic enters the bridge at an ingress port, passes through the 5GS and leaves the bridge at an egress port. TSN translators (TT) provide Ethernet/TSN ports towards the external network. Two types of ports can be distinguished: a device-side port is located at a mobile device that connects to a TSN end host or a downstream TSN network. A network-side port is provided at the 5GS gateway that connects to the fixed network, like a Ethernet/TSN backbone. The same 5G network can form multiple virtual bridges, each of which is realized via the UPF gateway instance in the 5G core network. A UPF configured for Ethernet/TSN support and all UEs connected to that UPF with Ethernet PDU sessions jointly form the virtual bridge and its ports. 5G contains a TSN-AF which provides the interface towards the TSN controller for bridge capability reporting and TSN configuration. As the 5G network is a larger distributed system, functionality related to TSN support need to be handled in various functions and locations of the 5G system. It is not sufficient to leave all internals of the virtual 5G TSN bridge for implementation. Therefore, 3GPP has specified e.g., how configuration information is signaled in-between the impacted network functions, like in-between the TSN translators and the TSN-AF. Also the policing and shaping of traffic according to the TSN configuration has been specified (see section 3.5), as well as the transfer of time synchronization via gPTP.

The ambition of 3GPP standardization has been to let the virtual 5G TSN bridge provide compatible interfaces towards the external nodes (via TT for user plane and via TSN-AF for control plane).

However, there exist significant differences in the characteristics between a virtual 5G TSN bridge and a wired TSN bridge:

- The *bridging distance* between an ingress and an egress port is significantly larger with a 5G virtual bridge compared to a wired bridge. In a wired bridge the bridging distance is in the order of a decimeter; in a virtual 5G bridge the distance is between the UPF and the UE, or in-between two UEs and can be up to 100's of meters or even kilometers. This can also have a significant impact on the *network topology*. In a wired TSN network, in order to connect two end points a chain of up to many 10's of hops via intermediate bridges need to be traversed for E2E connectivity. With a 5G virtual bridge only few hops can be expected: 1-2 (or up to a few) hops to reach the 5G ingress (UE or UPF) and 1-2 (or up to a few) hops to reach the end node from the 5G egress (UE or UPF).
- The *number of bridge ports* in a wired bridge is decided at the design and production of the bridge; bridge ports are at fixed locations (in the chassis of the bridge). In the virtual 5G bridge, the number of ports of the virtual bridge depends on the number of UEs connected to the UPF that defines the virtual bridge. Even if TSN-UEs can be considered as devices that are long-term persistently connected to the 5G network for providing TSN connectivity, it may be that a new UE is connected to the 5G network. A new UE might connect to the same UPF as other UEs, in which case the number of ports of this virtual bridge increases. As the bridge capability report of a bridge comprises the latency performance for all combinations of port pairs, a new connected UE may require a new interaction with the CNC for reporting bridge capabilities and receiving bridge configurations.
- The *latency characteristics* of the 5G virtual bridge may differ significantly from the latency characteristics of a wired bridge. The latency performance of a wired bridge is in the single-digit microsecond range, with a PDV in the range of some 100's of nanoseconds, see e.g., Figure 4.5. In a wireless TSN bridge the typical latency values are in the range of milliseconds and without specific configurations for low latency bounds they can reach up to some 10's of milliseconds. A more exhaustive description of latency breakdown – including latency options – for 5G can be found in [DET23-D21] section 2, with an example shown in Fig. 17 in [DET23-D21]. Even if an upper latency bound of the port-to-port latency through 5GS can be provided by according 5G features and appropriate configuration, it becomes clear that the PDV of a 5G virtual bridge is substantially larger than for a wired bridge.
- The *characteristics of a* (wired) *TSN bridge* are determined at design and production time. A wired bridge that is tested in a lab prior to normal deployment can be expected to behave in the same way during operations as during the lab test. In contrast, for a wireless system – and a virtual 5G TSN bridge – the performance depends on the radio environment and deployment (in particular for the radio access network (RAN)). This means that the characteristics of the virtual 5G bridge are determined during the operation phase. With a sufficiently well-planned and deployed RAN, the general 5GS performance can be expected to perform with similar performance like in a prior lab test, but it may need configuration to be adapted to the specific deployment. In case of major changes in the radio environment (e.g., walls or large blocking installations being added) changes in the performance might occur.

While the 5GS has been specified to be compatible to TSN by its external interfaces, the differences in characteristics of the virtual 5G bridge and a wired TSN bridge, and possibly also different deployment

topologies, motivate to investigate and review how TSN is configured and used most efficiently when wired and wireless TSN bridges are included.

3.4 Criteria for selection of the shaping and scheduling algorithms

IEEE defined a wide set of various shaping and E2E scheduling methods for TSN networks. 3GPP specification 23.501 has described only two methods (one for filtering and one for scheduling (Hold & Forward Buffering)), but their implementation details were left open by the specifications. This can be considered as a limiting factor during the selection of E2E deterministic functionalities if wireless segments are used in a TSN/DetNet network.

It is important to note here that the ultimate target of deterministic network design is the bounded forwarding parameters and not the maximum network throughput. This contrasts with the typical radio design and configuration, where optimization targets spectral efficiency of the wireless system. For non-deterministic traffic, spectral efficiency remains a main optimization goal but for time-critical traffic a separate 5G network configuration is needed with focus on latency-bounded performance. (Note: more details can be found in [DET23-D21] in section 2 dealing with a 5G latency breakdown.)

Typical inputs for the E2E deterministic design are the applications characteristics, the number of served streams/flows, their traffic descriptors, the deterministic traffic volume, and the co-existence with non-deterministic traffic in the same network.

Section 4 deals in detail with the general challenges of deterministic network design.

3.5 Application of traffic shaping mechanisms on 6G DetCom

3GPP document 23.501 defines the “Hold & Forward Buffering” method to shape the transmitted traffic. This function is envisioned to be supported at the DS-TT and NW-TT in order to mimic the behavior of scheduled traffic per traffic class at the “egress port(s)” of the wireless domain.

According to [3GPP23-23501], the hold and forward buffering mechanism provides externally observable behavior identical to scheduled traffic with up to eight queues (clause 8.6.8.4 in IEEE Std 802.1Q) and with protected windows (Annex Q.2 in IEEE Std 802.1Q). The buffer at the DS-TT or NW-TT holds the forwarded packets until their scheduled time, as shown in Fig. 3.3.

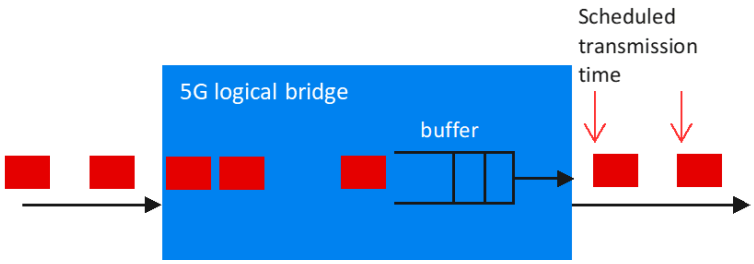


Figure 3.3: Traffic Shaping within the 5G/6G domain via the Hold & Forward Buffer

The Hold & Forward Buffer can be interpreted as a spin-off of the IEEE 802.1 Qbv method. However, 3GPP does not specify how the Hold and Forward buffers should be implemented. For example, assuming an IEEE 802.1 Qbv based implementation, the stream identification (and related priority settings), the design of gating cycle(s), their periodic/aperiodic characteristic, and correlation of gating cycle(s) and radio specific states/parameters are unclear.

4 Wireless-friendly, adaptive end-to-end scheduling algorithms

As described above, the DETERMINSTIC6G project aims at a revolutionary approach to the design, planning, and operation of time-critical networks that fully embraces the variability but also dynamic changes that come at the side of introducing wireless connectivity. In particular, stochastic components that lead to PDV significantly beyond what can be found in wired counterparts have been identified as challenging.

In this section, we consider novel algorithms to calculate wireless-friendly E2E schedules that explicitly consider stochastic PD with large PDV along an E2E communication path. In particular, we focus on so-called scheduled traffic in TSN specified in IEEE 802.1Qbv, which is often also referred to as Time-Aware Shaper (TAS). The TAS performs time-driven scheduling for a series of TSN bridges based on calculated scheduling time tables (gate control lists) that specify, when different egress queues of TSN bridges can forward frames. Obviously, this time-driven mechanism is directly affected by PDV in the data path, which can become large in wireless TSN bridges. This might lead to problems in real-time communication, in particular, violations of deadlines if the calculated schedule is not – informally speaking – ”wireless-friendly”, i.e., unable to cope with large PDV. Considering PDV requires fundamentally new concepts to enable dependable E2E communication, going significantly beyond the state of the art. Essentially, we need to go from a deterministic regime to a stochastic regime with new models to capture stochastic properties (such as PDV) and scheduling algorithms based on these new models. With respect to TAS, this means that the planning of time-driven schedules needs to be robust with respect to stochastic properties. This requires a fundamental shift from deterministic optimization approaches for calculating schedules to robust optimization with uncertain parameters – a research field that itself is relatively young in other domains such as operations research. However, although we first focus on the TAS, these fundamentally different stochastic properties are expected to impact all TSN scheduling approaches. In short, robust wireless-friendly E2E scheduling is nothing less than a paradigm shift from the deterministic regime with certain parameters to the stochastic regime.

In this section we will describe existing work related to TSN E2E scheduling, identify the problems arising from PDV, outline possible solutions to make time-driven Qbv scheduling wireless-friendly, and the information required for wireless-friendly scheduling transferred over the interface between TSN bridges and logically centralized network control (Centralized Network Controller).

4.1 Overview

To guarantee bounds on E2E PD and PDV, scheduling algorithms are required. The goal of these algorithms is to guarantee bounded queuing delay in network elements (bridges or routers), which is otherwise subject to variable cross traffic. Without packet scheduling, the queuing delay would be unpredictable and unbounded in general. By enforcing bounds on the queuing delay at each network element along the E2E path and adding the other factors of network delay, namely, propagation delay, processing delay, and transmission delay – which are independent of cross-traffic –, a bounded E2E network delay can be guaranteed.
The specific goal of this part of the DETERMINISTIC6G project is to design and implement *wireless-friendly* packet scheduling algorithms that consider the specific requirements of an E2E network path consisting of a combination of wired and wireless network elements (bridges and routers). The major challenge stems from the fundamentally different delay properties of wireless links. On the one hand,

wireless links exhibit significantly larger and heavy-tailed packet delay. State-of-the-art approaches for packet scheduling – in particular from the area of TSN, as discussed in more detail in the next sub-section –, assume wired links with narrowly bounded delays. Therefore, E2E scheduling approaches for time-driven scheduling, as specified in particular by the TAS of IEEE802.1Qbv – but also other scheduling mechanisms depending directly on time such as Cyclic Queuing and Forwarding (CQF) defined in P802.1Qch – for wired networks cannot simply be applied to wireless networks since they are based on fundamentally different assumptions. Instead, *packet scheduling algorithms that explicitly consider large PDV* are required. This also has implications on the control plane interface between network elements (bridges routers) and network control components calculating schedules, for instance, a CNC of a TSN network. The network elements must be able to provide the required information to the network controller to calculate wireless-friendly schedules. In particular, this information includes the individual PDV of network elements and their wireless links.

On the other hand, the packet delay of wireless links is dynamic and can change significantly over time due to factors like slow and fast fading, shadowing by obstacles, multi-path propagation, retransmissions for error recovery, etc. Such adverse effects are even stronger if mobile stations are considered. These variations need to be captured in the PDV for a virtual wireless TSN bridge appropriately. In contrast, the characteristics of wired links are assumed to be static, besides the possibility that links can fail completely, which typically is a rare event in wired networks. Designing packets schedules for the worst case would come with highly reduced utilization of precious wireless network resources and reduces scalability of the network. Instead, *adapting* the schedule over time when required (e.g., when the PDV changes significantly) is a more promising approach. Again, this has implications on the control plane interface between network elements and network control. Now, this interface must be extended to reactively inform network control about the current situation, e.g., using event-based mechanisms.

In the following, we discuss these aspects in more detail:

- Section 4.2 provides an overview and discussion of the state of the art in real-time packet scheduling.
- Section 4.3 introduces novel approaches and algorithms for wireless-friendly E2E scheduling with a focus on time-driven TSN scheduling as defined in IEEE 802.1Qbv.
- Section 4.4 presents and discusses enhancements to the control plane interface, i.e., how to present network elements towards the network controller.

4.2 State of the Art

In this sub-section, we present the state of the art in real-time E2E packet scheduling. The goal of the presented approaches is to guarantee a bounded queuing delay for each network element (bridges or routers) along the E2E path. Other factors of network delay (propagation delay, processing delay, transmission delay) are not subject to scheduling, but need to be considered when planning the E2E schedule. Note that this overview is focused on *end-to-end* guarantees rather than scheduling transmissions on a single wired or wireless link.

The following scheduling methods are typically used for E2E scheduling (just focussing on mechanisms for real-time communication aiming at bounded queuing delay):

- **Resource reservation** reserves network resources (bandwidth) at each network element along the E2E path. Bandwidth can either be reserved by allocating time intervals for streams when they can utilize the egress bandwidth (**time-driven scheduling**) or using **fair queuing** mechanisms that guarantee that each stream is served regularly such that it receives a well-defined portion of the egress bandwidth.
    - **Time-driven scheduling** (aka time-triggered scheduling, time scheduled traffic) requires the calculation of scheduling **time tables** that define when certain packets should be forwarded or queued to be served by bridges or routers to implement a Time-Division-Multiplexing-like scheme through the network. Prominent implementations of time-driven scheduling include the TAS (IEEE 820.1Qbv) and CQF (IEEE 802.1Qch) from IEEE TSN. The major challenge for time-driven scheduling is the **calculation of the time tables**, which for many scheduling problems is NP-hard, i.e., intractable for large problem instances with many streams, larger networks, etc. Therefore, exact (provable optimal) solutions often can only be found for few hundred streams in practice, and heuristic approaches are applied to find close-to-optimal solutions (see below for a more detailed discussion).
    - **Fair queuing** ensures that packets of queued streams are served regularly at each network element to receive a well-defined fraction of the total egress bandwidth. Additionally, the traffic of streams or queues is restricted, e.g., with respect to the average rate and burst rate and duration, using traffic shaping. A prominent example is the Guaranteed Services of the Integrated Services (IntServ) architecture, using Weighted Fair Queuing (WFQ) to reserve bandwidth per stream, and token buckets to shape ingress traffic. Also the CBS as defined in IEEE 802.1Qav is based on this principle, using Credit-Based Fair Queuing (CBFQ) to smooth out bursts through hop-by-hop shaping. Moreover, the Asynchronous Traffic Shaper is based on per-stream shaping at each hop along the path. Again, the challenge is the schedulability analysis given a set of streams with traffic specifications and scheduling parameters (e.g., reserved bandwidth at bridges or routers).
- **Priority-driven scheduling** assigns priorities to packets, either statically or dynamically, and always forwards the queued packet with the highest priority. A simple example of priority-driven scheduling with static priorities is Strict Priority Queuing. Other static priority-driven scheduling algorithms known from real-time task scheduling such as deadline monotonic assignment of priorities (priorities are defined based on the relative deadline of periodic tasks) or rate-monotonic assignment of priorities (priorities are defined based on the rate (1/period) of periodic tasks) are less common in networking and, therefore, are not considered further here. Similarly, many well-known priority-driven real-time task scheduling algorithms with dynamic priorities such as Earliest Deadline First (EDF) or Least Slack Time (LST), which define priorities depending on the current temporal distance to the deadline, are not commonly used for packet scheduling. The major challenge of priority-driven approaches is the **schedulability analysis**, i.e., answering the question: given a set of streams with their stream parameters such as period, deadline, frame count and size per period, and a priority-driven scheduling algorithm, is the given stream set schedulable, i.e., will all streams meet their deadlines?

From this classification of scheduling algorithms, it becomes clear that the complexity of E2E scheduling stems either from the calculation of a TDMA schedule (time table) for time-driven

scheduling or the schedulability analysis for the other scheduling algorithms relying on priorities, resource reservation, and traffic shaping.

In the following, we focus on the discussion of time-driven scheduling mechanisms as defined by TSN (IEEE 802.1Qbv), which poses the biggest and most obvious challenge when applied to wireless networks since they directly rely on time as means to trigger scheduling. We only briefly touch the state of the art in schedulability analysis. We focus our related work discussion on the question: are the current approaches wireless-friendly? In particular, this requires that approaches need to be robust in network environments with high PDV, which is fundamentally different from wired networks with – compared to wireless links – very predictable packet delay variation on links.

Calculating Time-Driven Schedules

The following discussion applies to different time-driven scheduling technologies such as the TAS as defined in IEEE 802.1Qbv. All of these approaches require calculation of a time table to trigger scheduling. This time table is then used by network elements to trigger packet scheduling in the data plane. For a precise discussion, we call the calculation of the time table the *schedule planning*, and scheduling packets in the data plane the *execution of the schedule*. Schedule planning requires sophisticated algorithms due to its complexity. Schedule execution requires accurate and precise clocks and time synchronization of network elements and for some traffic models such as isochronous traffic also end stations (talkers in TSN jargon) to synchronize forwarding along the E2E path. The following discussion is focussed on schedule planning; a more detailed discussion of time synchronization can be found in D2.2 *First Report on Time Synchronization for E2E Time Awareness* [DET23-D22] of WP2.

Current planning approaches for time-driven scheduling can be divided into two categories: scheduling-only approaches and Joint Routing and Scheduling (JRaS) approaches. Scheduling-only approaches only isolate streams in the time domain assuming given and fixed paths and “only” need to calculate the schedules (which by itself is already an NP-hard problem in general). JRaS considers the time and space dimension and needs to calculate both, time tables and paths for each stream.

Instead of striving for a comprehensive overview of existing planning approaches, we next aim for explaining the general principles (methods) and their problems in wireless systems with high PDV. For a current survey with an extensive presentation of existing approaches see [SOL+22].

Typical methods for schedule planning include among others Integer Linear Programming (ILP), Constraint Programming (CP), Satisfiability Modulo Theories (SMT), and various heuristics to speed up the planning process. The basic idea of all these approaches is to formalize the constraints for valid schedules and paths (for JRaS) as well as (optionally) add an optimization goal. A typical constraint for technologies like Ethernet is “no two frames must be transmitted over the same link (egress port) at the same time” (no temporal overlap) or the relative packet arrival time at the destination (listener) after the packet release time at the sender (talker) must be before the relative deadline. Such constraints are essential to calculate valid schedules that can actually be implemented in the network and meet time bounds. Optimization goals are often optional and can be used to further optimize the schedule, e.g., to minimize the inter-arrival jitter of packets from the same stream in different cycles of the hypercycle.

Whether an approach for planning time-driven schedules is suitable for wireless networks with high PDV shows in its assumption on packet delay and how these assumptions are reflected in the constraints and optimization goals of the scheduling problem formulation. An exemplary "no overlap" constraint from the ILP formulation of the "No-Wait Packet Scheduling Problem" for TSN from [DN16] is shown below:

$$\begin{aligned} if(b_{s,t}) \rightarrow start_{s,e} + d_{s.e,trans} \leq start_{t,e} \\ if(\neg b_{s,t}) \rightarrow start_{t,e} + d_{t.e,trans} \leq start_{s,e} \end{aligned} \quad (4.1)$$

For every combination of two streams, say s, t, let $start_{s,e}$ be the variable for the start of transmission time of stream s on link e (i.e. the time a network device starts transmitting stream s onto the link e) and let $d_{s.e,trans}$ be the transmission delay for the transmission of s on e. Furthermore, let $b_{s,t}$ be a binary decision variable deciding whether s is transmitted before t ($b_{s,t} = 1$) or t is transmitted before s ($b_{s,t} = 0$), i.e., a logical "or" constraint formulating that either s comes before t or vice versa. For two streams s, t this constraint ensures that the transmission of one stream is completed before the transmission of the other stream is started. Obviously, the transmission delay in this constraint is assumed to be constant.

Moreover, the start time on each link is calculated as the start time of the stream at the talker (which is a variable of the scheduling problem and calculated as a result of schedule planning), plus the cumulative network delay up to the start of transmission on the next link (cf. Fig. 4.1) – note that this approach implements a so-called "zero queuing" approach, where packets are forwarded immediately when they are enqueued into the egress queue of a bridge with zero queuing delay, therefore, no queuing delay is shown in the figure. Thus, the following constraint is added to the ILP:

$$start_{s,ei+1} = start_{s,ei} + d_{transmission} + d_{propagation} + d_{processing}$$

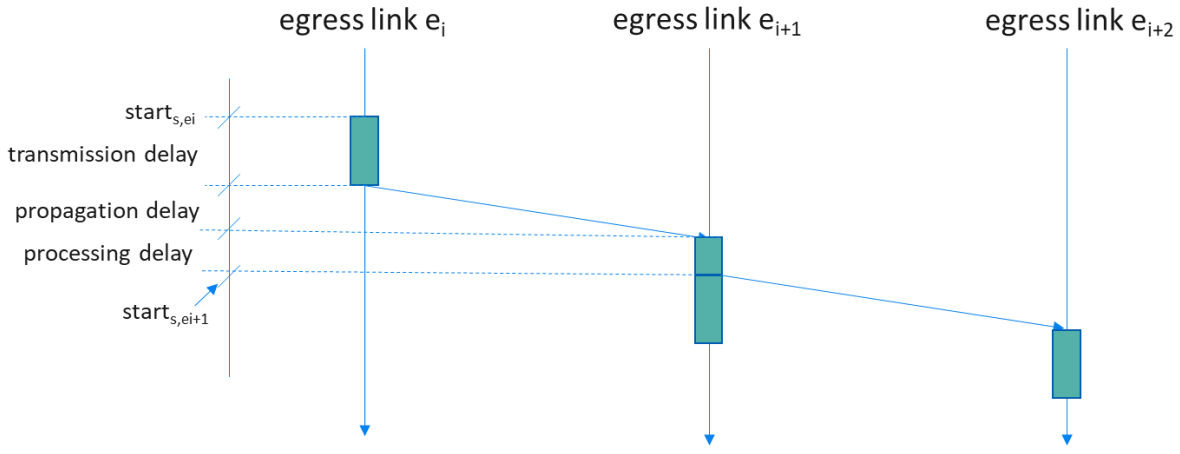


Figure 4.1: Calculation of start times based on constant delays

Here, the transmission delay, propagation delay, and processing delay are assumed to be constant. The assumptions of constant delays, however, is unrealistic, already for wired networks but even more so for wireless networks. Therefore, the practicality of this and similar approaches can be challenged already for wired networks, although the problems might be easier to handle for wired networks in

comparison to wireless networks since small additional margins might “solve” the problem. However, this example also highlights the coarse abstraction of delay and strong assumptions that many scheduling approaches make by assuming strictly deterministic behaviour. Moreover, it highlights the large research gap that has to be bridged to design robust wireless-friendly schedules that can deal with stochastic delays. In this example, stochastic delay with PDV leads to variable delays between starting the transmission on one link and enqueuing the packet into the egress queue of the subsequent bridge. Therefore, also the start times on consecutive links are not constant anymore but follow the PDV distribution. Applying such a formulation to wireless networks can have severe consequences such as adding unforeseen additional delay and even reordering of packets, again increasing delay of some packets.

In addition, the specific optimization goal of this approach aims at compact schedules, with packets scheduled back-to-back. Obviously, with such a schedule, additional delays from one packet will directly delay subsequent packets scheduled back-to-back. In summary, this example shows that such as schedule is not robust to any PDV beyond constant delay.

A first observation is that the assumption of sharply defined PDVs with hard bounds on narrow delay intervals or even constant delays as in this example is unrealistic for wireless networks. However, this is a very common assumption for wired scheduling beyond this specific example. Wireless-friendly algorithms must explicitly consider broader PDV distributions that are typically heavy-tailed.

A second observation is that this example and also any other approach that we reviewed do not explicitly consider reliability as KPI, defined as a ratio of packets being delivered in time (e.g., 99.999 % of packets meeting their deadline). The common assumption is that the network is reliable or there is sufficient redundancy in the network, e.g., through packet replication and disjoint paths, such that a correct schedule can deliver all messages within their deadlines and failures are negligible. Since 100 % reliability is unrealistic under the assumption of heavy-tailed PDVs, new wireless-friendly algorithms should explicitly consider reliability requirements striving for a defined fraction of packets being delivered within given time bounds. The definition of the reliability must be rooted in the PDVs (provable reliability).

Another important aspect of wireless-friendly schedules is their ability to cope with dynamic environments with evolving PDVs. So far, the major cause for dynamic changes considered by schedule planning is the addition and removal of streams at runtime. Incremental scheduling approaches have been proposed in the literature, which avoid a complete replanning when streams are added or removed, e.g. [NDR17]. One step further, novel planning algorithms explicitly strive for flexibility to accommodate new streams in the future [GRK+23]. However, adapting an existing schedule to a new situation with changing PDVs has not been considered so far due to the assumption that the wired network is sufficiently reliable with constant data rates and delays. These assumptions need to be challenged in a wireless-friendly system, and novel scheduling approaches are required that can adapt at runtime to dynamic PDVs. Although one can try to make IEEE 802.1Qbv schedules robust to large PDVs, there might come the time when a replanning of the schedule is required, which is a costly operation due to the NP-hard nature of scheduling problem. This leads to various research questions:

- How can the robustness of E2E schedules be maximized such that they can last long without changes to limit the required adaptions at runtime?
- How can E2E schedules be calculated efficiently in short time when adaptation is required?
- Can the adaptation of E2E schedules be triggered proactively in advance to compensate for the inevitable lead time of schedule calculation (utilizing delay prediction mechanisms also developed in this project)?

Schedulability Analysis

Given the traffic specification of individual streams and the parameters related to resource reservation in the network (e.g., WFQ weights and bandwidths or CBFQ idle and send slopes), a formal worst-case analysis of the total maximum queuing delay can be performed. A typical framework for such an analysis is the network calculus, but in order to get an intuitive idea of such methods, we explain a simplified analysis of a single router using IntServ Guaranteed Services and a stream shaped by a token bucket with parameter *r* (token rate in bits per second) and *b* (bucket size in bits). The peak data rate of the ingress link of the router is denoted as *p*.

The basic idea is to define: (a) the service curve of a router to express the minimal (worst-case) resources (data rate *R*) that the router provides to the stream for forwarding; (b) the arrival curve defining the worst-case arrival of data at the router subject to token bucket traffic shaping. Looking at Fig. 4.2, we can see how to derive the worst-case backlog of the stream and maximum queuing delay d_{queue}^{max} from the service and arrival curves as show in Equation (4.2):

$$d_{queue}^{max} = \frac{pb}{R(p-r)} - \frac{b}{p-r} = \frac{pb-Rb}{R(p-r)} = \frac{b(p-R)}{R(p-r)} \quad (4.2)$$

At time *t0*, the first bit arrives at the router and more bits follow at peak rate *p* until at time *t1* the token bucket is depleted, and the rate is reduced to the sustained rate *r* of the token bucket. Note that this analysis assumes a fluid model with bits flowing in and out of the router, and the router processing bits immediately. In practice, the router queues and transmits packets. The effects of packetization are not shown here. The maximum queuing delay of a bit in the queue is given by the largest horizontal distance between the arrival curve (bit arrived at router) and the service curve (bit forwarded by the router). In the figure, this is the interval between *t1* (last bit of worst-case burst arrived at router) and *t2* (last bit of burst forwarded by router). The backlog is the number of bits queued by the router, and the maximum backlog is the largest vertical distance between arrival curve and service curve. Note that although this analysis can be used to determine the required worst-case buffer size per stream of a router, large buffers are not the solution to our problem since they can lead to the so-called bufferbloat problem, causing excessive queuing delay and delay variation.

As shown in RFC 2212 [SPG97], value d_{queue}^{max} can be further refined by taking other factors into account such as breaking down IP packets into smaller cells or time slots for a time-multiplexed network service.

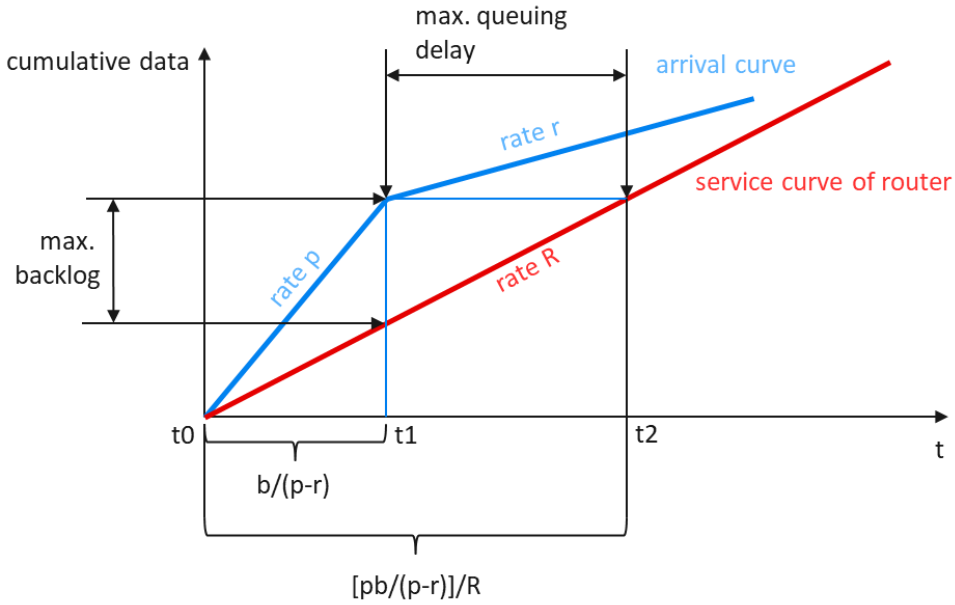


Figure 4.2: Analysis of maximum queuing delay and backlog

As we can see from this example, the analysis is only focused on the worst-case queuing delay. The stochastic effects of the PDV, which contributed substantially to the E2E delay, are not explicitly considered, as also stated by RFC 2212:

"In brief, delay has two parts: a fixed delay (transmission delays, etc) and a queueing delay. The fixed delay is a property of the chosen path, which is determined not by guaranteed service but by the setup mechanism." [SPG97]

This exemplary statement also shows a common assumption: the delays other than the queuing delay are assumed to be *fixed*. This overly simplistic assumption neglects the dynamic stochastic properties of PDV in wireless networks. It is obvious that any schedulability analysis for wireless networks must explicitly consider such stochastic PDVs.

Since, in this deliverable, we focus on time-driven real-time scheduling according to IEEE 802.1Qbv (Time-Aware Shaper), where the calculation of time schedules using constrained optimization techniques ensures meeting all timing constraints rather than performing a schedulability analysis for the schedule, we refrain from going into more detail about schedulability analysis here. However, we might revisit these techniques and discuss this in more detail when considering non-time-driven, priority-based approaches such as CBS or ATS in a future deliverable.

4.3 E2E Traffic Management and Scheduling for 6G Wireless Node

Next, we consider in more detail the problem of planning wireless-friendly E2E schedules for time-driven packet scheduling and the calculation of robust schedules under PDV. In particular, we focus on calculating schedules for the TSN Time-Aware Shaper (IEEE 802.1Qbv) in a network including wireless 6GDetCom nodes with large PDV by a centralized network controller (CNC) with global view onto the network.

Large stochastic PDV leads to different specific problems for time-driven E2E scheduling. We identify these problems and explain each problem and outline their solutions in separate sub-sections.

4.3.1 Stream Isolation

In the TSN model, multiple streams of the same priority share the same egress queue. Each egress queue is controlled by a gate that opens or closes according to a timetable (gate control list). Enqueued packets of the same egress queue are transmitted in FIFO order. Consequently, a packet, say Pkt B, that is enqueued after another packet, say Pkt A, can be held back by Pkt A, or in other words, the queuing delay of Pkt B depends on the other packets enqueued ahead of Pkt B in the same queue. It is the responsibility of the calculated schedule to ensure that this queuing delay is bounded such that packets meet their deadlines.

As already mentioned in the related work discussion, existing approaches for planning schedules assume that all other delays besides queuing delay – such as processing, transmission, and propagation delay – are strictly bounded (intervals with hard bounds) or simply constant. With stochastic packet delay, this assumption does not hold anymore such that packets might arrive outside their anticipated time window at bridges. Since packets from different streams share the same egress queue, a late packet might delay other packets from other streams in the same queue. If late packets push other packets beyond their anticipated time windows, streams are not sufficiently isolated in time anymore. In the worst case, a domino effect starts, where in a sequence of P1, P2, P3, … of packets enqueued in the same egress queue, the delayed packet P1 delays the subsequent packet P2, P2 delays P3, etc. Also, buffers might overflow, leading to congestion loss – a situation that TSN, aiming at zero congestion loss, explicitly tries to prevent.

Consider the example of a 6GDetCom node (wireless TSN bridge) in Fig. 4.3. The 6GDetCom node includes two UEs, each connected to a TSN bridge of a wired TSN network. For instance, this could be TSN bridges of two Automated Guided Vehicle (AGV) to which all devices of the AGV connect. The bridges of the AGVs are each connected via a wireless link to the 6GDetCom node. We assume that two talkers, say Talker A and Talker B, send two Packets, say Pkt A and Pkt B, upstream towards the 6GDetCom node. Another wired port of the 6GDetCom node is connected to a fixed wired TSN network on the right-hand side, where the listeners for the Talker A and Talker B reside. We assume that Pkt A and Pkt B have the same priority, and, therefore, will be enqueued into the same egress queue towards the fixed network.

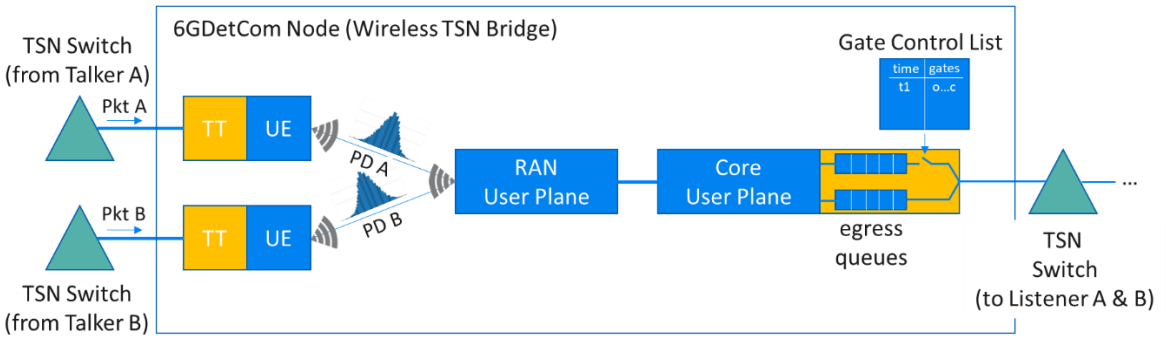
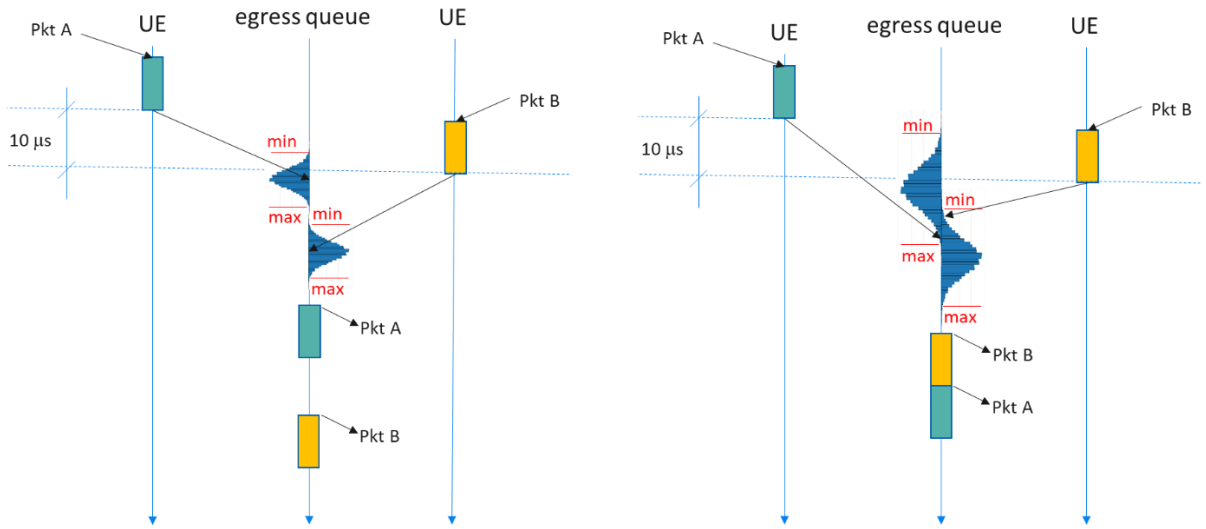


Figure 4.3: 6GDetCom node connecting two TSN networks of two AGVs (left-hand side) to a fixed network (right-hand side)

On the wireless links, Pkt A and Pkt B are delayed with some packet delay distributions (PD A, PD B). Assume that Pkt A arrives at the UE of the 6GDetCom node 10 µs before Pkt B. Figure 4.4(a) shows the scenario with small PDVs, where the intervals of the two PDVs do not overlap. In this case, Pkt A will be definitely enqueued into the egress queues before Pkt B. Figure 4(b) shows the same scenario, but now with larger, overlapping PDs. Now, with a certain probability, Pkt B will be enqueued into the egress queue before Pkt A and delays Pkt A.



(a) Pkt A enqued definitely before B (b) Pkt B overtakes Pkt A and delays Pkt A

Figure 4.4: Packet forwarding with PDV

In Figure 4.4(b), we assume that the delayed Pkt A can still be transmitted during the same open-gate cycle. The additional delay would have been even higher if Pkt A had to wait until the next open-gate cycle. Moreover, other packets might have been scheduled for transmission in the next open-gate cycle, which also will be delayed by a late packet from the previous cycle. Therefore, even "old" packets from a stream (from the previous cycle) might now delay "new" packets from the same stream. This effect of a long so-called busy period is also known from task scheduling if deadlines of jobs from a periodic task are longer than the task period. In the worst case, delays might keep growing if packets from old cycles start accumulating in queues, and eventually queues might overflow leading to packet loss. This shows that delayed packets can have severe consequences for a non-robust schedule.

One approach to deal with this problem is to protect streams from very late or also early packets from other streams, i.e., to enforce isolation in time. The standard IEEE 802.1Qci *Per Stream Filtering and Policing* defines mechanisms to enforce stream isolation. So-called stream gates can be used to drop frames that arrive outside of their anticipated time windows before they can harm other streams at the egress queue. Effectively, the tail of the PDV could be "cut off" using filtering, however, at the expense of packet loss (also see next sub-section). So, one obvious requirement for wireless-friendly schedules is to calculate the configuration of stream gates to protect streams from each other together with the schedule.

4.3.2 Wireless-friendly, Robust End-to-End Scheduling

Although dropping packets that jeopardize the timely delivery of other streams can isolate streams from each other, dropping packets should only be the last resort. What we are really aiming at are robust schedules that, informally speaking, operate correctly with non-negligible PDVs. The notion of correctness deserves some discussion. Since PDVs theoretically might be unbounded – with a (small) probability, packets can be very late –, we cannot require anymore that all packets arrive within their deadlines. Instead, we use the notion of reliability defined as the ratio of packets arriving within their deadline to all packets. We define per-stream reliability as the reliability of an individual stream.

A schedule can either optimize reliability or guarantee reliability. Different optimization goals can be defined such as:

- Maximize the overall reliability (maximize sum of per-stream reliability).
- Max-min reliability: maximize the reliability of the stream with the least reliability.

Optimization of robustness might be beneficial to maximize the chance that a schedule calculated for the current situation will also be applicable in case PDV becomes worse over time. In other words, the current schedule could be used for as long as possible without adapting and re-calculating schedules, which is, as explained already above, a costly operation due to the high complexity of calculating schedules.

If reliability has to be guaranteed, then a minimum acceptable reliability (reliability bound) can be defined per stream as constraint. Per-stream bounds can also be specified in addition to one of the optimization goals, requiring that a certain minimum per-stream reliability has to be guaranteed and beyond these constraints, reliability is considered as optimization objective, e.g., to make the schedule as robust as possible.

The following approach can be used for both, guaranteeing and optimizing reliability. The basic idea of the approach is to add maximum temporal distance (guard bands) between packets. Intuitively, this should make it less likely that an early or late packet interferes with another packet. The scheduling problem of maximizing the guard bands can be formally described as an ILP as follows:

For two streams s, t and a network link e, the variable $gap_{s,t,e}$ shall be the time difference between the completed transmission of one stream and the transmission start of the next stream. Note that with stochastic delay distributions, these gaps are expressed in terms of the expected values of the distributions since ILPs cannot express probabilities. With the binary decision variable $b_{s,t}$, we can define a new set of constraints providing an upper bound for $gap_{s,t,e}$:

$$\begin{aligned} if\left(b_{s,t}\right) &\rightarrow gap_{s,t,e} \leq start_{t,e} - end_{s,e} \\ if\left(\neg b_{s,t}\right) &\rightarrow gap_{s,t,e} \leq start_{s,e} - end_{t,e} \end{aligned} \quad (4.3)$$

We can now use these upper-bounded gap variables to maximize the robustness of a schedule by maximizing the gap variables. To this end, let G be the set of all gap variables for all combinations of two distinct streams and one network link. There are multiple possible objectives which aim to maximize the gap between variables. One way is to maximize the sum of all gap variables $g \in G$:

$$maximize\left(\sum_{g \in G} g\right) \quad (4.4)$$

Another, more sophisticated approach is to maximize smallest gap $maxizmize\big(min(G)\big)$. However, as ILPs do not have a minimum function, we need another variable $g_{min} = min(G)$ and upper bound it by the smallest g using the following constraint:

$$\forall g \in G : g_{min} \leq g \quad (4.5)$$

And then define the optimization objective to maximize g_{min}:

$$maximize(g_{min}) \quad (4.6)$$

Although this approach maximizes the robustness of a schedule under PDV, more sophisticated approaches for wireless-friendly scheduling are desirable as shown in the next sub-section.

4.3.3 Resource Utilization vs. Reliability

Increasing the robustness of schedules and reliability of streams meeting their deadlines by adding guard bands as described in the previous sub-section does come at a cost. By adding guard bands around packet transmissions to avoid interference with other early or late packets, resource utilization (bandwidth that can be utilized) and scalability (number of real-time streams that can accepted) are reduced since during guard bands, no other real-time transmissions than for the reserved stream are allowed – concurrent low-priority traffic could still be forwarded, in particular, if frame preemption is applied, but also comes at an overhead since frames in transmission cannot be preempted at arbitrary positions during transmission. In other words, this approach aims at reserving time intervals for the transmission of packets that do not interleave (zero-interleaving). However, if the PDV is large – which is typically the case for heavy-tailed distributions as measured for wireless networks – compared to the actual duration of transmission, most of the reserved time interval is not utilized. On the one hand, this shows that such a zero-interleaving approach is very conservative and designs the schedule such that streams do not interfere with close to 100 % probability. On the other hand, it sacrifices efficiency in terms of resource utilization, even if interference is uncritical, i.e., the additional delay might not actually lead to deadline violations or only with sufficiently small probability, which might be still within the required reliability specifications of the application.

This shows that there will not be a one-size-fits-all solution for E2E scheduling, but the approach needs to be tailored to the given constraints and optimization objectives. Therefore, more approaches, besides the approach presented above using guard bands, will be developed during the project runtime to guarantee reliability while maximizing efficiency.

4.3.4 Accumulated Delays and Convolution of Packet Delay Distributions

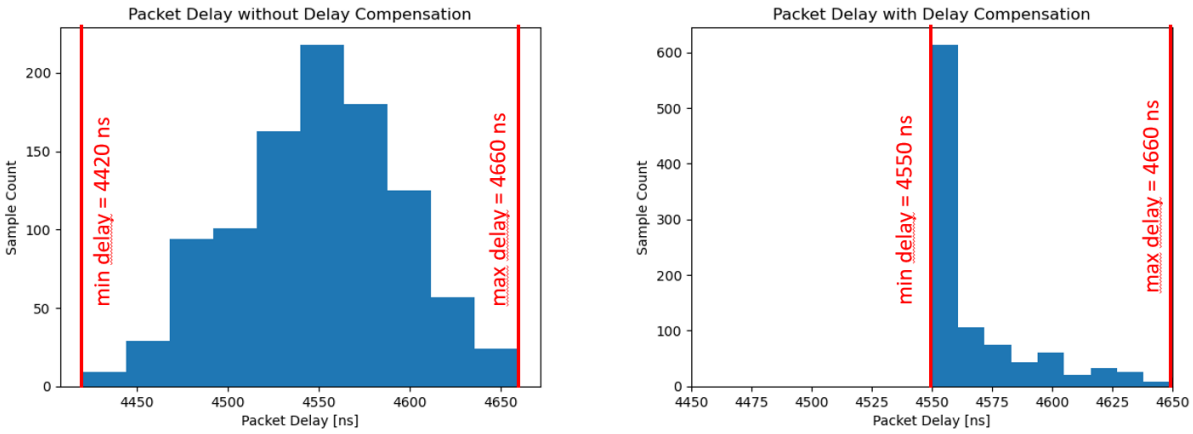
Another specific problem in wireless networks with larger PDV is that the uncertainty along an E2E path with multiple wireless nodes increases towards the end of the path. Formally, the packet delay distributions per bridge along the path add up, and the total E2E PD distribution is the convolution of all packet delay distributions along the path. In practice, the number of wireless hops will be small, in many scenarios not exceeding one or two wireless hops. Although we expect that such cases with multiple wireless hops along a path are less common that a single wireless hop, for a rigorous analysis

and guarantees that applications can depend on, it is still necessary to consider the general case of multiple wireless links and the convolution of packet delay distributions along an E2E path.

Assume an E2E path with two wireless hops at the 6GDetCom nodes N1 and N2. Let the PD distributions of N1 and N2 between ingress and egress ports be both normal distributions, denoted as $P_{X1} = N(\mu_1,\sigma_1^2)$ and $P_{X2} = N(\mu_2,\sigma_2^2)$, respectively. Then the two-hop PD distribution after the egress port of N2 is the convolution $P_{X1X2} = P_{X1} * P_{X2}$ of P_{X1} and P_{X2}. Although the convolution is not straightforward to calculate, for normal distributions, the convolution is simply $P_{X1} * P_{X2} = N(\mu_1+\mu_2,\sigma_1^2+\sigma_2^2)$. This shows that not only the expected delay $\mu_1 + \mu_2$ increases, but also the variance $\sigma_1^2 + \sigma_2^2$. In plain words, the PD distribution becomes wider and the uncertainty increases.

This increase in uncertainty has severe consequences for a time-driven TSN schedule. To avoid dropping packets and impacting packets from other streams, the expected time window of arrival (stream gates) and for forwarding (gate schedule) have to be increased along the path. Or in terms of the zero-interleaving scheduling approach presented above, the guard bands have to be increased. This impacts the utilization and robustness of the schedule (cf. Sec. 4.3.2 and Sec. 4.3.3). For an intuitive analogy, compare this to scheduling trains at a train station, say Munich. If trains from Stuttgart to Munich are often delayed, it will become very difficult to calculate a schedule when the train should leave Munich. This difficulty lies in the fact that the variability of delays increases with each hop introducing more uncertainty. Scheduling would be much easier if all trains from Stuttgart arrived in Munich at a precisely defined point in time rather than within a large time interval.

The solution to this problem is to transform the broad distribution after each wireless link into a sharp(er) distribution with smaller variance. The basic idea to implement this is to artificially hold back early packets at bridges to equalize the delay of early and late packets. This transforms the shape of the PD distribution as shown in Fig. 4.5. The numbers in Fig. 4.5(a) are based on measurements with a wired TSN bridge, i.e., the delay distribution expected for a wireless TSN bridge is even higher than the shown PDV. The compensated delay in Fig. 4.5(b) has been calculated offline. Holding back packets, in general, will increase the individual and average delay of packets since some packets are deliberately delayed, but reduces delay variance. This trade-off between increasing delay and reducing variance has to be considered in E2E scheduling. On the one hand, delaying packets too aggressively with a too high hold back time might make it impossible to meet tight deadlines. On the other hand, holding back too reluctantly increases PDV with all its negative consequences for scheduling as discussed already above. An approach has to be found that applies the right level of delay.



(a) PDV (min,max) = 240 ns (b) PDV (min,max) = 110 ns

Figure 4.5: PDV of a wired TSN bridge (a) without delay compensation; (b) with delay compensation

There are two approaches to hold back packets, namely, through the TSN TAS (gating mechanism) or using a special mechanism called Packet Delay Correction (PDC). The TAS can hold back packets in egress queues using the standard TSN gating defined in IEEE 802.1Qbv. To this end, the gate opening time will be defined through the E2E schedule such that a packet of a stream has arrived with sufficiently high probability under PDV, before opening the gate, which has e.g. been applied in [KAJ+22]. However, this approach has severe disadvantages since the number of egress queues is limited to, at maximum, eight. Therefore, in general, many streams share the same egress queue, and holding back early packets of one stream might delay packets of other streams enqueued behind the held back packet (head of line blocking). There might be workarounds for this problem, like schedules that only allow for a single packet to be queued at a time in each egress queue. However, such workarounds always come with severe implications like limited scalability. Therefore, a dedicated mechanism in the data plane to hold back packets outside egress queues seems to be the more attractive approach.

PDC is such a dedicated mechanism for holding back packets. PDC has been described in technical detail in Deliverable: D2.1: *First Report on 6G Centric Enablers* [DET23-D21] of WP2. Therefore, we only describe PDC here briefly to keep this document self-contained. PDC holds back packets in the data path of a wireless TSN bridge until a specified release time after the ingress port and before packets are enqueued into the egress queues of the bridge. This is a major difference to holding back packets in the egress queue using the TSN gating mechanism. With PDC, packets of individual streams can be hold back without interfering with other streams, i.e., without adding additional head of line blocking. From the point of view of the E2E schedule, the PD distribution of individual streams is transformed into another PD distribution with longer delay and less variance, without side-effects onto other streams, which reduces the complexity of E2E scheduling since delay compensation is none of its concerns (no degree of freedom of the scheduling problem) anymore. Therefore, within this report, we do not consider a dedicated scheduling approach that compensated for delays in the schedule, but rely on PDC. This problem might be revised later, if scheduling and the parametrization of PDC are considered as a joint problem.

4.4 Representation of 6G system towards CNC/SDN

As becomes obvious from the description of the wireless-friendly E2E scheduling in the previous sub-sections, the calculation of time-driven schedules requires information from the 6G system at the centralized 6GDetCom controller. Therefore, one major question is, which information needs to be exposed by the 6G system, in particular, 6GDetCom nodes (wireless TSN bridges) to the 6GDetCom network controller (CNC in TSN jargon)?

As also described above, another major requirement of wireless-friendly E2E scheduling is the ability to adapt to the dynamic state and properties of the wireless 6G system, which is only predictable up to a certain time horizon with sufficient accuracy and precision in practice. This adaptation requires a novel or extended interface between 6G system and 6GDetCom controller to enable reactive (re-)planning. With the knowledge of the new information to be exposed by the 6G system and the extended interface required for reactive E2E scheduling, we can define how the current standards need to evolve to enable wireless-friendly E2E scheduling.

From the discussion above of how to calculate wireless-friendly schedules, it is obvious that the **PD distribution and their PDV** is crucial for planning time-driven schedules, which happens in the control plane at the 6GDetCom controller (CNC as shown in Fig. 3.1). One proposal is that 6GDetCom nodes inform the 6GDetCom controller about the current PD distribution in the data plane. For instance, the 6GDetCom node could measure the current PD distribution at runtime an offer a control plane interface to query the PD distribution. The concrete format of how PD distributions are presented to the 6GDetCom controller can vary, including histograms based on measurements or simply an interval bounded by min-max delay values, together with the cumulative probability of packet delays being within this interval. Since the PDV can vary in upstream and downstream directions and between different pairs of ports of the 6GDetCom node, PD distributions should be reported per port-pair and direction. If PD distributions vary by stream, group of streams, or priority or streams, even more fine-grained PDV reports per stream, stream group, priority, etc. are beneficial to allow for precise schedule planning.

Adaptation to new situations requires that the 6GDetCom controller and the logic for schedule planning implemented at the controller knows the **time horizon** until which the reported PD distribution can be considered valid ($t_{expiration}$ in Fig. 4.6). Such a time horizon facilitates implementation of polling schemes, where the network controller can poll new PD distribution values from the bridges using a request/response mechanism as can be implemented using, for instance, the Simple Network Management Protocol (SNMP), NETCONF, or RESTCONF, i.e., common control plane interfaces of TSN bridges. Polling might require some lead time (d_{lead} in Fig. 4.6), to poll PD distributions in advance before they expire since schedule planning is a computational complex task as already mentioned. This is shown in Fig. 4.6 where the controller starts polling $d_{leadtime}$ before the expiration time $t_{expiration,i}$ of the old PD distribution PD_i and its corresponding schedule S_i, in order to calculate a new schedule S_{i+1} before the old PD distribution PD_i and schedule S_i become invalid at time $t_{expiration,i}$.

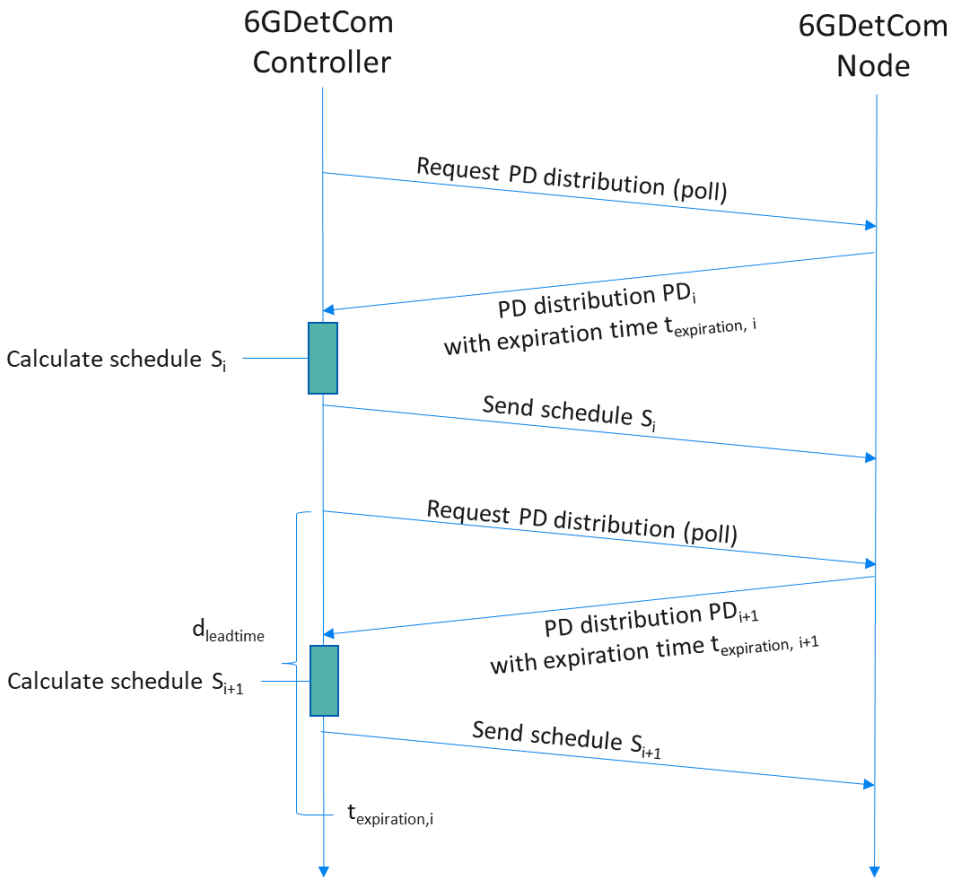


Figure 4.6: Polling PD distribution periodically with time horizon of validity and lead time

A more elegant and efficient approach in terms of communication overhead is the implementation of an **event-based publish/subscribe interface** between 6GDetCom controller and 6GDetCom nodes, which eliminates the need for periodic polling. With such an interface, the network controller could subscribe to updates of the PD distribution at 6GDetCom nodes, and receive notifications when PDV values change significantly. Again, the time required to calculate schedules has to be considered in such an event-based interface, such that updates can be requested with a certain lead time when PD distributions are expected to change some time in the future.

One option is to perform packet delay correction in the 6G system (i.e. the 6GDetCom node) as described in [DET23-D21]). In this case a simple implementation would just report the compensated PD distribution through the interface described above. However, more sophisticated interactions between schedule planning and PDC could be implemented with novel interfaces between 6GDetCom controller and 6GDetCom node. If an interface is in place to parametrize PDC, e.g., the hold-back time of packets, the joint configuration of schedules and PDC could be defined as an extended planning problem. Such extended problem formulations and the required control plane interfaces will be reconsidered, after the basic schedule approaches for planning schedules with PDVs have been designed.

5 Conclusion & Future Work

Dependable communication standards are being developed to ensure data delivery in a reliable and timely fashion. The IEEE 802.1 community is playing a central role in developing these standards to provide guaranteed high performance connectivity services for certain traffic flows on a common Layer-2 Ethernet. Moreover, dependable time-critical transport solution over Layer-3 routed networks to ensure bounded latency and low data loss is being specified under the IETF DetNet standardization. While these standardization efforts in wired networks are being carried out, the flexibility of wireless communication motivated provisioning of dependable communication over wireless networks through TSN integration with 5G under 3GPP Releases 16, 17 and 18. 5G support for DetNet is also specified in 3GPP Release 18. The 5G support for TSN and DetNet are built on the 5G URLLC capabilities introduced in 3GPP Release 15.

The ongoing work here is to add further enhanced functionalities to 5G/6G systems to be able to cope with more extreme-requirements scenarios. Future work can be expected within some of these topics: TSN profiles (e.g., IEC/IEEE 60802, P802.1DG), protection for time synchronization (P802.1ASdm), and configuration (e.g., P802.1Qdj, P802.1Qdd, P802.1Qdx, P802.1Qdy, P802.1ASdn) related standards, new projects on Cut-Through Forwarding Bridges and Bridged Networks (P802.1DU) and on enhancements to queueing (P802.1Qdv). Furthermore, work is expected to make TSN solutions easily available for non-bridge devices (P802.1DC). Work is in progress on the controller plane framework, scalability requirements and new queueing techniques to provide controlled PDV.

Regarding the RAP amendment, this report provides an overview of its developments which is still under standardization but is being designed to support dynamic resource management and admission control for distributed TSN configuration model. The functionality extension for 6G virtual bridge as a support for integration with TSN in distributed configuration will be considered as part of the future work.

Moreover, this report provides details on wired and wireless dependable communication standardization efforts that will serve as enablers of 6G convergence for E2E dependable communication. Many open questions and specification gaps on TSN/DetNet interfacing with 6G wireless nodes, configuration protocols, 6G network exposure capabilities, and information exchange between the wired and wireless domains are highlighted that needs further investigation for seamless integration and E2E deterministic communication support. Furthermore, the report highlights that the enhancements or detailed interactions of existing 5G functionalities such as the TSCTSF for control/management plane communication need to be developed further for 6G systems. While this deliverable reports on gap analysis and future directions on envisioned E2E dependable communication support in 6G, details on traffic shaping concepts and E2E scheduling algorithms are also discussed.

TSN and DetNet related functionalities of 5G were defined with a primary focus on latency and reliability. These enhancements made 5G ready to cover deterministic network scenarios, where latency and resiliency requirements are not stretched to extreme values. The area of covered scenarios and the settings of TSN and DetNet related functions need further validation in practical operation. Also, the efficiency of 5G at scale - when connected to a larger TSN network - needs to be further investigated. Scenarios with extreme requirements will require further functionalities from wireless systems.

Regarding TSN/DetNet-related network functionalities three future directions were defined to overcome the limitations inherited by wireless systems. Direction-1: Enhance “virtual TSN/DetNet node” characteristics. This direction mitigates the characteristics difference of the “virtual node” and focuses on solutions to fix the wireless specific characteristic. This direction focuses exclusively on the wireless domain and its internal functionalities. Direction-1 is part of another deliverable [DET23-D21] and will be further investigated in the rest of the project timeline. Direction-2: Incorporate wireless specifics. This direction improves the existing E2E deterministic communication design/tools to tolerate wireless specifics. This direction focuses on improved building blocks that can be used E2E. Direction-3: Being wireless-friendly. This direction intends to evolve the deterministic toolset with new building blocks that have wireless-friendly operation/characteristics. While the 5GS has been specified to be compatible to TSN/DetNet by its external interfaces, with the advent of more wireless-friendly solutions further work is needed to define new ways to expose 6G networks. Directions -2 and -3 are covered in this deliverable and will be developed in a future deliverable.

The differences in characteristics of the virtual 5G/6G bridge and a wired TSN bridge and also different deployment scenarios trigger further investigations, e.g., to review how TSN/DetNet is configured and used most efficiently when wired and wireless nodes co-exist in a network scenario.

With respect to wireless-friendly E2E scheduling, we have proposed a first approach in this report that optimizes the robustness of time-driven scheduling according to IEEE 802.1Qbv for wireless systems with high stochastic PDV (or mixed TSN networks with wired and wireless nodes). This approach makes a first step from the strictly deterministic regime commonly assumed for calculating schedules for wired networks to the stochastic regime, which due to its novelty provides plenty of opportunity for future research. However, this proposed approach based on zero-interleaving time intervals when forwarding streams is very conservative (often too conservative), since it tries to minimize the interference of streams independent of whether this interference would actually lead to deadline violations with respect to application requirements. Therefore, it is at one end of the spectrum of planning wireless-friendly schedules making robustness a first-class citizen at the cost of reduced resource efficiency.

Therefore, one of our ongoing work in the area of wireless-friendly E2E scheduling is to improve the algorithms for planning time-driven (IEEE 802.1Qbv) schedules such that stochastic reliability requirements are fulfilled while network resources are optimized. In plain words, the idea is to allow for interleaving time intervals while forwarding packets whenever (and only if) this will not significantly compromise the adherence to deadlines, i.e., deadline violations are sufficiently seldom such that reliability requirements are fulfilled. PDV needs to be considered in a rigorous approach to provide provably correct (dependable) schedules. To this end, we will further consider approaches from related research areas such as robust optimization that deal with the general problem of planning with uncertain parameters.

As another direction of future research for wireless-friendly scheduling, we will consider non-time-driven scheduling approaches besides time-driven scheduling (IEEE 802.1Qbv). It is obvious that time-driven scheduling will be affected by PDV since it directly depends on time to make scheduling decisions. Other scheduling approaches, for instance, based on priorities or queuing mechanisms, might be more robust. TSN already defines alternative scheduling mechanisms, including credit-based shaping (based on credit-based fair queuing) or asynchronous traffic shaping. We will investigate the applicability of these methods to our problem (scheduling under stochastic delays), but also consider

the combination of these methods and the design of other scheduling mechanisms tailored to our E2E scheduling problem.

A further future direction for E2E scheduling is to consider the problem of adapting schedules at runtime to dynamically changing conditions, in particular, changing delay distributions. Several problems make dynamic adaptation at runtime challenging: (1) Calculating new schedules (e.g., time tables for IEEE 802.1Qbv) takes significant time. How can we reduce the time to calculate schedules by designing efficient heuristic approaches (instead of relying, for instance, on exact but slow ILP solvers)? How can we trigger schedule planning proactively ahead of time considering predictions of delay distributions? (2) Changing schedules of already existing streams is non-trivial and might lead to interruptions during the transition to a new schedule. Can we design incremental scheduling approaches that bring in new streams at runtime without affecting the schedule of already scheduled streams?

Finally, we plan to consider E2E scheduling beyond a single domain. One important question that arises is: How can we split the E2E budget between domains, also considering the uncertainty of the (partial) delay within a domain?

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List of abbreviations

3GPP	3rd Generation Partnership Project
5GS	5G System
5QI	5G QoS identifier
AP	Attribute Propagation
AVB	Audio Video Bridging (AVB)
ATS	Asynchronous Traffic Shaper (IEEE 8021.Qcr)
BoF	Bird of a Feather
CBFQ	Credit-Based Fair Queuing
CBS	Credit-Based Shaper (IEEE 802.1Qav)
CNC	Centralized Network Controller
CP	Constraint Programming
CPS	Cyber Physical System
CQF	Cyclic Queuing and Forwarding (IEEE 802.1Qch)
CUC	Centralized User Configuration
DetNet	Deterministic Networking
DS-TT	Device-Side TSN Translator
E2E	End-to-End
EDF	Earliest Deadline First
FRER	Frame Replication and Elimination for Reliability
ICT	Information and Communication Technology
IETF	Internet Engineering Task Force
ILP	Integer Linear Programming
IP	Internet Protocol
IntServ	Integrated Services
JRaS	Joint Routing and Scheduling
KI	Key Issue
KPI	Key Performance Indicator (KPI)
LAA	Listener Attach Attribute
LDACS	L-band Digital Aeronautical Communications System
LRP	Link-local Registration Protocol
LRPDU	LRP Data Units
LST	Least Slack Time
ML	Machine Learning
MPLS	Multi Protocol Label Switching
MSRP	Multiple Stream Reservation Protocol
MRP	Multiple Registration Protocol
MVRP	Multicast VLAN Registration Protocol
NEF	Network Exposure Function

NR	New Radio
NW-TT	Network-Side TSC Translator
OAM	Operations, Administration, and Maintenance
OFDM	Orthogonal Frequency Division Multiplex
PDC	Packet Delay Compensation
PDU	Packet Data Unit
PD	Packet Delay
PDV	Packet Delay Variation
PLC	Programmable Logic Controller
PTP	Precision Time Protocol
QoS	Quality of Service
RA	Resource Allocation
RAN	Radio Access Network
RAP	Resource Allocation Protocol (IEEE 802.1 Qdd)
RCT	RA Class Template
SDN	Software-Defined Networking
SLA	Service Level Agreement
SMF	Session Management Function
SMT	Satisfiability Modulo Theories
SNMP	Simple Network Management Protocol
SRP	Stream Reservation Protocol (802.1Qat)
TAS	Time-Aware Shaper (IEEE 802.1Qbv)
TDMA	Time Division Multiple Access
TG	Task Group
TAA	Talker Announce Attribute
TLV	Type-Length-Value
TSC	Time Sensitive Communication
TSCH	Time-Slotted Channel Hopping
TSCTSF	Time Sensitive Communications and Time Synchronization Function
TSN	Time-Sensitive Networking (IEEE 802.1)
UE	User Equipment
UPF	User Plane Function
URLLC	Ultra-Reliable and Low Latency Communication
WFQ	Weighted Fair Queuing
WG	Working Group

Table 1: List of abbreviations