DETERMINISTIC6G

Final Project Report

D6.4

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Final Project Report

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Revision History

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V1.0	Final document

Disclaimer

Executive summary

In this final project report of DETERMINISTIC6G the main achievements and results of the project are summarized. For all work packages, the main achievements are explained and the key takeaways are highlighted, as well as references to all deliverables are provided. All work packages of the project are completed successfully, the corresponding objectives towards 6G-enabled dependable, time-critical communication have been reached – in some cases the conveyed results have been overachieving the originally planned tasks. The project's main achievements include the detailed description of local- and wide-area use cases, where time-critical communication and compute are essential. The significant work of the project covers the development of enhanced 6G functionalities to ensure improved time-awareness, as well as extension of legacy TSN/DetNet systems with capabilities to integrate wireless systems with stochastic characteristics into the end-to-end system design. Together with project activities in the areas of security, digital twinning, dependable compute and the extensive validation of the developed concepts, DETERMINISTIC6G has delivered a comprehensive set of solutions for end-to-end dependable, time-critical communication for 6G visionary use cases.

Contents

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 "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 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 of systems. New techniques based on Machine Learning 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 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 end-to-end KPI (e.g., minimum and maximum packet delay) 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.

DETERMINISTIC6G is a European Union funded project that started off on the 1st of January 2023 and lasting 30 months plus 3 months of extension for dissemination purposes. The total project budget was roughly 5.5 million Euros and with around 21 full-time person equivalents working during the project duration from 12 partners and 2 linked partners.

The primary objective of the DETERMINISTIC6G project is to define essential architectural principles and describe new conceptual solutions as enablers towards the E2E dependable, time-critical communication to be provided by the 6G ecosystem. To achieve this goal, the DETERMINISTIC6G project applies a combination of complementary approaches, such as a) tightly integrating the system elements with stochastic characteristics (e.g., wireless and compute components) into a dependable system design, and as b) mitigating the stochastic uncertainties in the communication and compute components. Following this approach, Figure 1-1 shows the scope of the project and the major project goals.

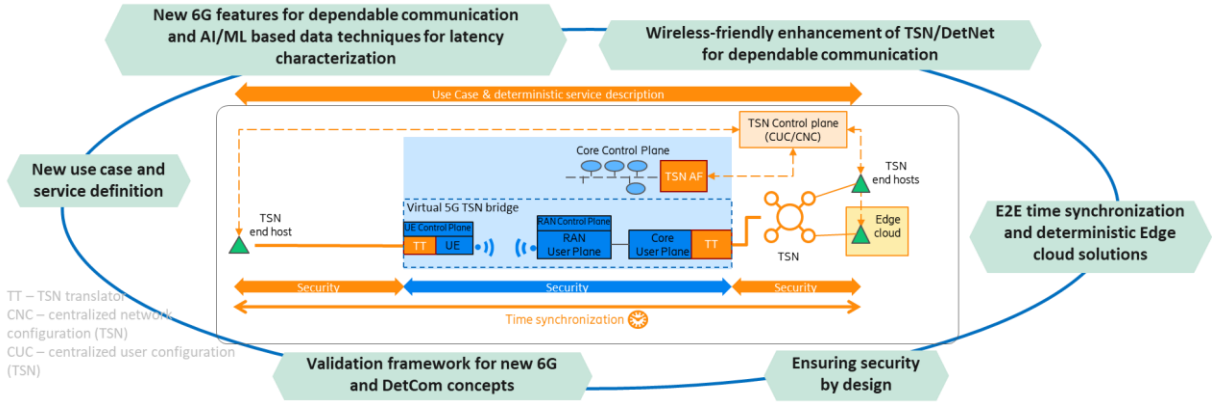


Figure 1-1: DETERMINISTIC6G project goals

Figure 1-2 shows the structure of the project, reflecting the different focus areas of the targeted work and showcases the work packages addressing them.

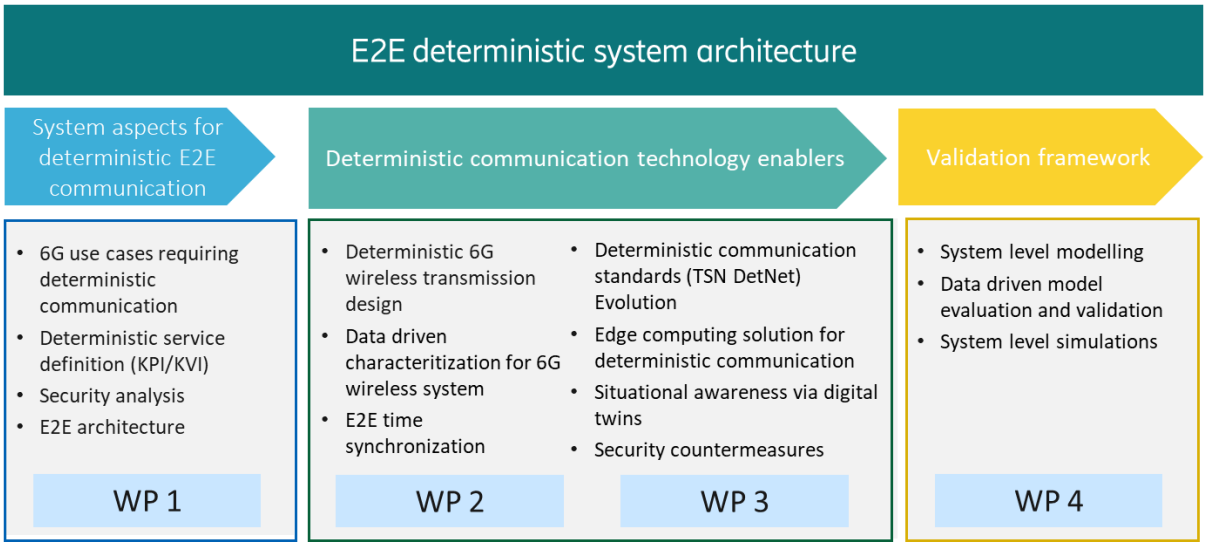


Figure 1-2: DETERMINISTIC6G project structure

The major focus areas of the DETERMINISTIC6G project are as follows:

- Description and characterization of various use cases, where dependable, time-critical communication is essential.
- Development of a novel dependable service design framework.
- Definition of an E2E dependable architecture framework, by identifying and describing the necessary components to ensure dependable service operation.
- Development of 6G centric enablers for ensuring dependable, time-critical communication services, by considering the use case requirements. This target covers the development of various packet delay correction (PDC) solutions, data-driven methods for latency characterization and prediction in 6G systems, robust time synchronization for E2E time-awareness, as well as resource allocation strategies in RAN.
- Further developing the existing deterministic communication systems (e.g., IEEE 802.1 Time Sensitive Networking – TSN, IETF Deterministic Networking - DetNet) to enable them to consider the stochastics behavior of the 6G wireless networks in the most efficient way.

- Developing wireless-aware, E2E traffic scheduling concepts covering multiple technology domains (e.g., wired TSN, 6G).
- Development of edge computing features to ensure the support of predictable operation and the seamless integration of edge computing deployment with TSN.
- Development of a security-by-design framework, focusing on real-time monitoring and attack detection.
- Situational awareness via digital twinning of the 6G system
- Development of a simulation framework to enable the realistic E2E simulation of an integrated wired and wireless TSN deployment (with stochastic packet delay characteristics) to enable the extensive validation of the developed technical concepts.

1.1 Objective of the document

This document aims to summarize the main results and achievements of the DETERMINISTIC6G project. It provides an overview of the project upon its completion with the key takeaways and contains references to the most important outputs of the project.

1.2 Structure and scope of the document

This document is structured as follows: Section 1 gives an introduction to the deliverable. Section 2 discusses the DETERMINISTIC6G approach towards converged future infrastructures for scalable cyber-physical systems deployment. Section 3 provides insights into the achievements of DETERMINISTIC6G in the areas of use cases description and dependable service design, and also provides an overview of the dependable 6G architecture components. Section 4 focuses on the results achieved regarding 6G-centric enablers for dependable, time-critical communication, such as RAN latency characterization and prediction, packet delay correction, RAN resource management and reliable time synchronization. Section 5 gives an overview of the results in the areas of wireless-aware system design, time-aware edge computing deployment, security design, as well as situational awareness via digital twinning. Section 6 provides a comprehensive overview of the concept validation methodology and results. Section 7 presents the dissemination and communication efforts in the project, while Section 8 concludes the document.

2 DETERMINISTIC6G approach

Time-critical communication has in the past been mainly prevalent in industrial automation scenarios with special compute hardware like Programmable Logic Controllers (PLC), and based on proprietary, mutually incompatible wired communication technologies, such as Powerlink and EtherCat, which are limited to local and isolated network domains and which are configured to the specific purpose of the local applications. With the standardization of TSN and Deterministic Networking (DetNet), similar capabilities are being introduced into Ethernet and IP networking technologies, which thereby provide a converged multi-service network enabling 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. Furthermore, using interchangeable TSN hardware components has economic benefits, avoids vendor lock-in, and enables third-party support for configuration and troubleshooting.

It turns out that 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 that for compute and communication elements and also applications 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 computing, but introduces uncertainty in execution times; wireless communications provide flexibility and simplicity, but with inherently stochastic components that lead to packet delay variations 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. It turns out that these deviations of stochastic characteristics make traditional approaches to planning and configuration of end-to-end 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 computing, and application innovation. DETERMINISTIC6G has as objective to address these challenges, including the planning of resource allocation for diverse time-critical services end-to-end, over multiple domains, providing efficient resource usage and a scalable solution [SPS+23].

DETERMINISTIC6G takes a novel approach towards converged future infrastructures for scalable cyber-physical systems 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 end-to-end 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 for allowing adaptation between applications running over 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 end-to-end KPIs, and (b) possibly can adapt end-to-end 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, a notion of deterministic communication (where all behavior of network and compute nodes and applications is pre-determined) is extended 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 end-to-end, across domains and including 6G.

3 Use cases, service design aspects and architecture for dependable E2E time-critical communication with 6G

A solid conceptual and architectural foundation is needed to enable the usage of future 6G networks for dependable, end-to-end (E2E) time-critical communication within the next generation of industrial and cyber-physical systems. The DETERMINISTIC6G project established such foundations by identifying and analyzing visionary use cases – such as XR, exoskeletons, adaptive manufacturing, and smart farming – to derive technical requirements, including performance indicators, compute offloading needs, and security constraints. These insights informed a value-driven service design framework that links technical capabilities with societal impact, emphasizing adaptability, resilience, and sustainability.

A major achievement of the work is the proposal of a comprehensive architecture that integrates wireless and wired domains (e.g., TSN and DetNet), supports real-time edge computing, and enables observability and prediction of network performance using AI/ML. It also embeds security-by-design principles and supports flexible service provisioning through application-communication-compute co-design and seamless evolution from 5G to 6G. The architectural vision and service design methodology developed served as a cornerstone for technical developments and validations within the project.

3.1 Use cases

As illustrated in Figure 3-1, the DETERMINISTIC6G project explored four visionary industrial use cases — Extended Reality (XR), Exoskeletons in the industrial context, Adaptive Manufacturing, and Smart Farming — to understand and validate the requirements for dependable, end-to-end communication in future 6G networks. These use cases revealed the need for ultra-reliable, low-latency communication, edge computing integration, and adaptive service provisioning. The findings of this initial step have been documented in a dedicated report [DET23-D11].

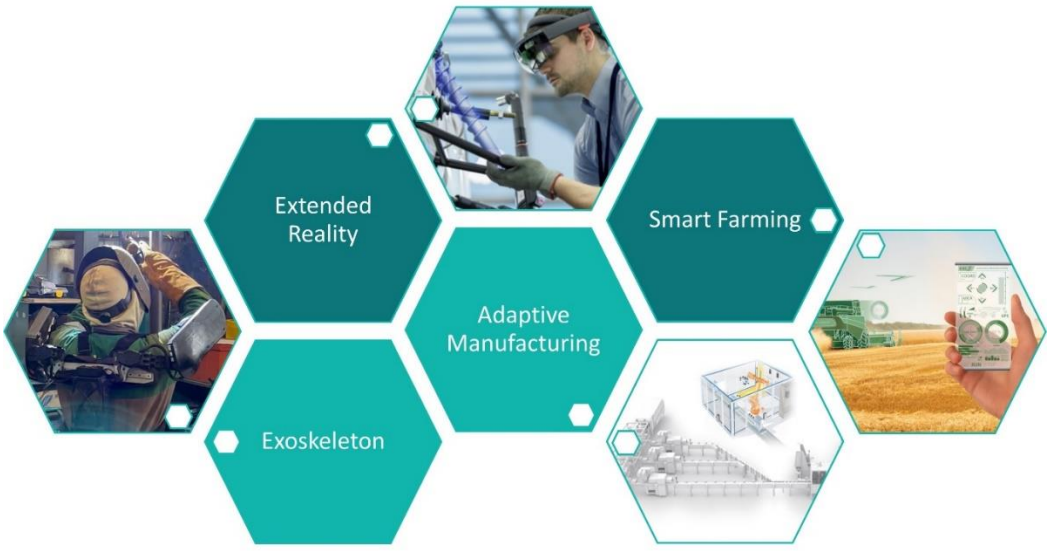


Figure 3-1: DETERMINISTIC6G use cases

In the XR use case, the integration of immersive technologies into industrial environments is seen as a powerful enabler for training, maintenance, and collaboration. The key takeaway is that offloading

computationally intensive tasks such as rendering and spatial computing to the edge or cloud can significantly reduce device complexity and improve user experience. However, this introduces stringent requirements on communication networks, particularly in terms of latency, jitter, and reliability. The dynamic nature of XR applications also demands adaptive service provisioning and fine-grained control over network resources.

The use case about exoskeletons in the industrial context highlights the potential of wearable robotics to reduce physical strain on workers and enhance productivity. These systems rely on real-time data exchange between on-board sensors, cloud-based controllers, and smart factory infrastructure. The presented scenarios emphasize the importance of dependable communication to ensure safety and responsiveness, especially when control loops are offloaded to the cloud. It also introduces the concept of operational modes, such as a safe fallback mode in case of degraded network performance, underscoring the need for robust and adaptive communication strategies.

Adaptive manufacturing represents a shift toward highly flexible and reconfigurable production systems. The use of mobile processing modules, collaborative robots, and digital twins enables rapid adaptation to changing market demands and product customization. The key insight here is that dependable communication is essential for coordinating mobile and stationary components, ensuring functional safety, and maintaining high throughput. The scenarios demonstrate how different operation modes and levels of service can be dynamically managed based on network conditions and application requirements.

Smart farming extends the concept of dependable communication to mobile automation in agriculture. Autonomous ground and aerial vehicles collaborate to perform tasks such as harvesting, monitoring, and treatment. It is illustrated how real-time coordination, remote control, and edge-based analytics can enhance efficiency and sustainability. It also addresses the challenges of operating in open environments with limited infrastructure, highlighting the need for resilient and secure communication systems.

Across all use cases, the project introduced a value-driven service design framework that links technical capabilities with societal impact through Key Value Indicators (KVIs), addressing goals such as sustainability, safety, and inclusion. Finally, the use cases validated the vision of 6G systems as an architectural core technology for future industrial applications by enabling dependable E2E communication, supporting real-time edge computing, digital twins, and providing security-by-design.

3.2 Dependable service design

The work on dependable service design, as documented in Deliverable D1.3 [DET25-D13], focused on establishing a comprehensive, value-driven framework that aligns technological capabilities with industrial and societal priorities such as productivity, sustainability, and worker safety. A central achievement was the development of a structured methodology for designing adaptive and dependable services that can dynamically respond to the stochastic and time-sensitive nature of 6G environments. This was accomplished through the introduction of two key concepts: modes of operation, which are driven by application-level changes, and levels of operation, which are determined by infrastructure-level capabilities. These concepts enable dynamic service adaptation, ensuring that critical applications maintain optimal performance and reliability even under changing conditions.

A major technical contribution was the specification of dependable subservices – i.e., communication, computation, time synchronization and cyber security –, each characterized by parameters such as latency, availability, reliability, and maintainability. These subservices are designed to be composable, enabling applications to request complex service bundles tailored to their specific operational requirements. This is exemplified in Figure 3-2, where a factory floor is depicted, on which different communication services are required in the distinct areas and applications. The additional implementation of a value and cost function framework allows applications to express their operational value and resource needs in a machine-readable format. This enables the system to prioritize applications based on their contribution to overall system value, taking into account economic, societal, and environmental factors.

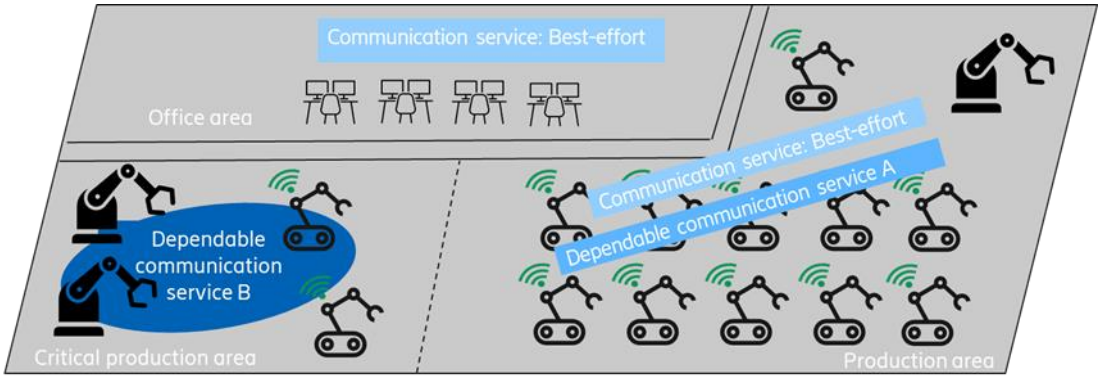


Figure 3-2: Factory floor with different communication services (Source: Ericsson)

The framework supports automated decision-making for resource allocation and service adaptation, ensuring that high-priority applications receive the necessary resources while maintaining system-wide efficiency. It allows to automatically respond to triggers from applications, infrastructure, or the environment to ensure that services can be reconfigured in real time to maintain dependability and optimize performance.

Furthermore, a co-design methodology for communication, computation, and control (3Cs) was introduced, which enhances system performance by leveraging the interdependencies between these domains. This approach supports more efficient resource utilization and enables the deployment of applications that would otherwise be infeasible due to stringent performance requirements.

3.3 DETERMINISTIC6G architecture

In order to enable dependable communication for time-critical services, like for the use cases described above, several components are required, as indicated in the subsequent chapters. All system components need to be aligned and integrated into an overarching system architecture, as indicated in Figure 3-3. The report [DET25-D14] describes a system design with a dependable 6G network architecture that integrates functionality for dependable time-critical services as developed in DETERMINISTIC6G. The proposed architecture integrates robust time synchronization (see Section 4.4), packet-delay control reducing large packet delay variations (see Section 4.2), builds on data-driven latency prediction (see Section 4.1) and integrated time-aware edge computing (see Section 5.3), and considers security-by-design principles for dependable time-critical services (see Section 5.4). The novel interactions among the different functional building blocks, as well as the way in which the applications can invoke dependable communication services, are also described. Furthermore, novel E2E traffic management for TSN and DetNet is described (see Sections 5.1 and 5.2) that operates

in conjunction with 6G wireless communication and virtualized application design, and improves E2E dependable networking. It is demonstrated in [DET25-D14] how the architecture framework is applied in order to realize the DETERMINISTIC6G use cases, which include local deployments on an industrial shopfloor, but also deployments over wider areas.

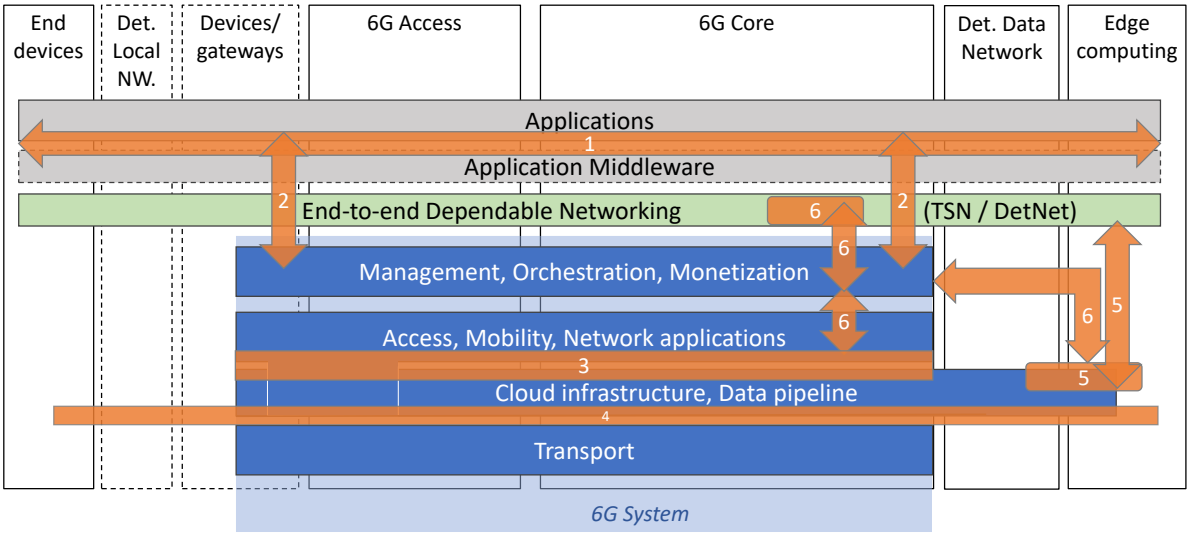


Figure 3-3: A 6G network enabling dependable time-critical communication end-to-end. Orange arrows indicate where functionality for dependable 6G network design developed in DETERMINISTIC6G are integrated into the system architecture (for details see [DET25-D14]).

3.4 Key takeaways

Future 6G networks must support high availability and low latency for applications like adaptive manufacturing, smart farming, extended reality (XR), and occupational exoskeletons. However, existing 5G architectures and wired time-sensitive network technologies (i.e., TSN and DetNet) require enhancements for handling stochastic behaviors introduced by wireless links, cloud computing, and dynamic applications.

These needs are addressed by the developed dependable service design framework and the proposed architecture, which integrates AI-driven performance prediction, packet delay correction, and robust time synchronization. Edge computing is tightly coupled with the network to enable dependable compute services for virtualized applications. Furthermore, it embeds security-by-design concepts and enables situational awareness via digital twins.

4 6G centric enablers for dependable, time-critical communication

Future 6G networks are expected to play an important role in offering dependable and time-critical connectivity service. Such services will be crucial for many emerging use cases such as adaptive manufacturing and mobile automation, extended reality, and occupational exoskeletons, as envisioned in [DET23-D11]. These use cases require stringent guarantees on Packet Delay (PD) and Packet Delay Variation (PDV), as well as a reliable and secure time synchronization. Enabling these capabilities in 6G will be crucial to fulfill the future requirements of these use cases.

4.1 RAN latency characterization and prediction

6G systems are today subject to spatial and temporal stochastic variations that need to be accurately characterized dynamically. To this end, data-driven latency characterization approaches have been proposed and evaluated.

4.1.1 Data-driven 5G latency characterization using mixed density distributions

Latency prediction for 5G systems was investigated as a general Conditional Density Estimation (CDE) problem, where the objective is to obtain the PDF[1] of latency given a certain system state. A Mixture Density Network (MDN) was derived to combine Gaussian Mixture Models (GMMs) with Generalized Pareto Distribution (GPD) to capture both the bulk region as well as the tail region of the latency PDF which is essential to predict high quantiles of latency [DET23-D21]. The proposed latency prediction approach was used to propose a new scheme for Active Queue Management (AQM). Incorporating PDF predictions in AQM algorithms that are otherwise configured with a predefined threshold can be very useful. In this way we can obtain a policy that maximizes the expectation of successful packets (i.e., packets processed before deadlines) by deciding about dropping some of the packets of the stream. The simulation results revealed that using packet drop policies derived from the Delay Violation Probabilities (DVPs) obtained from data-driven latency predictions results in overall improvement in packet success probabilities as compared to state-of-the-art AQM schemes such as CoDel and DeepQ.

The data-driven latency prediction approach was also evaluated on real wireless networks setups: (i) on Commercial off-the-shelf (COTS) 5G and (ii) Open Air Interface (OAI) 5G deployments. The results demonstrated that GMM combined with GPD (denoted as GMEVM) has much better performance in predicting the marginal PDF of uplink latency in COTS 5G than plain GMM (see Figure 4-1). Using data collected from the OAI 5G setup, the performance evaluation was performed in the context of conditional scenarios and a more challenging latency profile. Here, the performance of MDN models was evaluated in predicting latency PDF conditioned on Modulation and Coding Scheme (MCS) index and the role of noise regularization was highlighted.

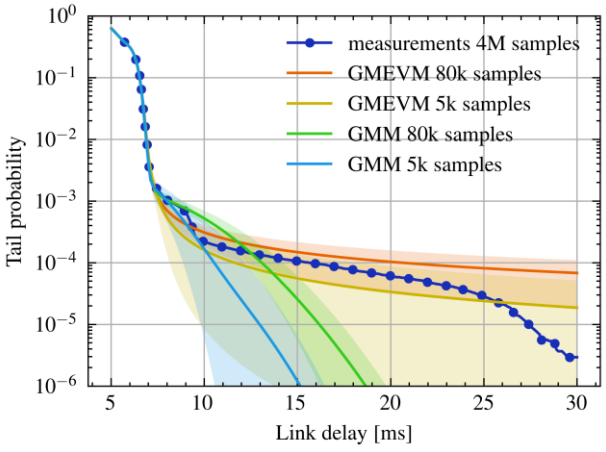


Figure 4-1: COTS 5G uplink latency measurements vs parametric density fits with different number of samples and models.

[1] Probability Density Function

4.1.2 Predictability framework

A formal definition of predictability in systems research is introduced [DET25-D23], which comprises understanding a system to be predictable (or more predictable) if out of current system state a different stochastic behavior can be deduced than what would be deduced from steady state conditions. Systems where current conditions do not allow any more refined stochastic characterization than what can be deduced for steady state are termed unpredictable. We show that under this definition bounds on the predictability can be derived for a wide class of Markovian systems. The analysis is validated numerically.

In the numerical analysis we further study the consequences of the definitions and the bounds with respect to Markovian queuing systems. We show that predictability decreases with longer prediction time horizons, while generally speaking more extreme instantaneous system states (like long backlog) lead to a higher predictability. Imprecise system knowledge (for instance due to unknown partial backlogs in multi-hop systems) leads interestingly only in some cases to a degradation of predictability, while outdated system state knowledge is equivalent (in terms of predictability implications) with considering longer time horizons.

4.1.3 Probabilistic latency prediction for wireless networks

Unlike traditional TSN, where packet delays are predictable and tightly bounded, 5G/6G introduces stochastic variations due to channel fading, interference, and retransmissions. We presented a deep-learning-based framework capable of incorporating Multi-Layer Perceptrons (MLPs), Long Short-Term Memory networks (LSTMs) and Transformers to predict the full probability distribution of end-to-end delays rather than just point estimates [DET25-D23]. By leveraging historical network states and encoding them into tokenized representations, the proposed approach provides multi-step probabilistic delay predictions, enabling adaptive scheduling and resource allocation. The evaluation on an SDR-based 5G testbed demonstrates that the Transformer model significantly outperforms traditional methods in capturing both short- and long-term dependencies in delay variations. This methodology is particularly valuable for 5G/6G-TSN integration, where ensuring deterministic latency over inherently variable wireless links is critical for applications like industrial automation, real-time control, and autonomous systems.

4.1.4 Overhead modeling for learning architectures

A performance model is proposed which allows the quantification of 5G/6G system variables on the total training time under either federated learning or centralized learning [DET25-D23], see Figure 4-2.

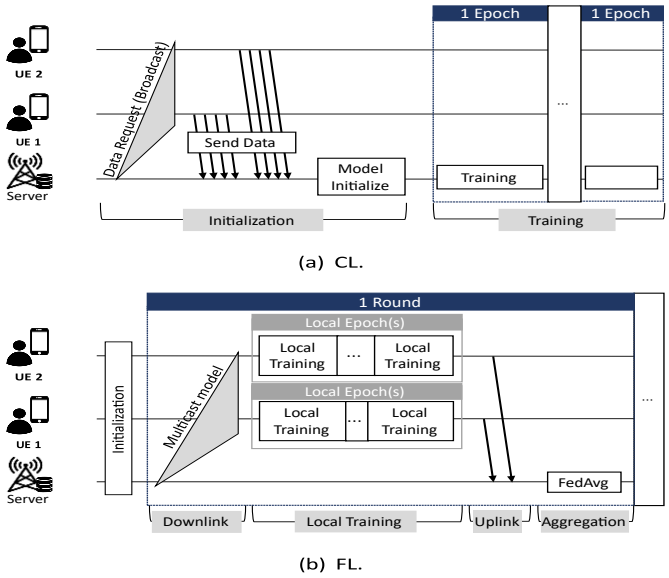


Figure 4-2: Learning procedures for the two learning schemes

The main factors influencing total training time are bandwidth, channel quality, data and model size as well as epoch choice in case of federated learning. Interestingly, in case of centralized learning only few single parameters already have a large impact on total training time, while for federated learning the impacts are distributed over more single parameters and parameter combinations.

More detailed performance studies reveal that no straightforward rules exist when either centralized or federated learning is advantageous. For instance, as bandwidth increases, depending on the data size, either centralized or federated learning have better training times (while for very high bandwidth federated learning always outperforms centralized learning). A key parameter is the choice of the local epoch in federated learning, which can drastically lead to longer training times.

4.1.5 Observability for delay performance and prediction

In order to provide a dependable communication service for time-critical applications, the 6G network needs to be able to quantitatively ascertain that it fulfils the application requirements on delay and packet delay variation. A fundamental capability for quantitative service provisioning is the capability of the network to observe the delivered delay performance.

The observed delay performance can be used for multiple purposes:

- to track and account for the delivered service performance, which may be needed to report on the fulfilment of a service level agreement,
- to provide a data basis for delay prediction,
- to reveal delay performance characteristics to other network domains (e.g., the TSN or DetNet domain) to facilitate multi-domain end-to-end dependable network services,
- to derive resource management strategies to ascertain the performance promises that have been made,
- in case that the performance delivered by the network is at risk of not being able to deliver on the performance goal, to interact with the application domain to facilitate application adaptations towards other levels of operation or modes of operation that still allow for acceptable operation of the application.

In a mobile network, two distinct sub-domains of delay performance can be distinguished, the core and transport network, and the radio access network; those can practically be managed distinctly in their dependable service provisioning. The 6G edge-to-edge delay performance is typically dominated by the radio access network, where novel approaches for dependable communication services are needed; for the core and transport network, established traffic engineering methods for fixed networks can provide a solid basis.

For the RAN we propose a delay-aware design [DET25-D23], where observability of delay performance can be integrated into the 6G radio protocols, e.g., based on the inherent time synchronicity of the radio interface operation. We propose the base station to collect delay performance for uplink and downlink transmission over the RAN, and make this data available for data-driven delay prediction, enhanced with information about the operational state of the RAN, as shown in Figure 4-3.

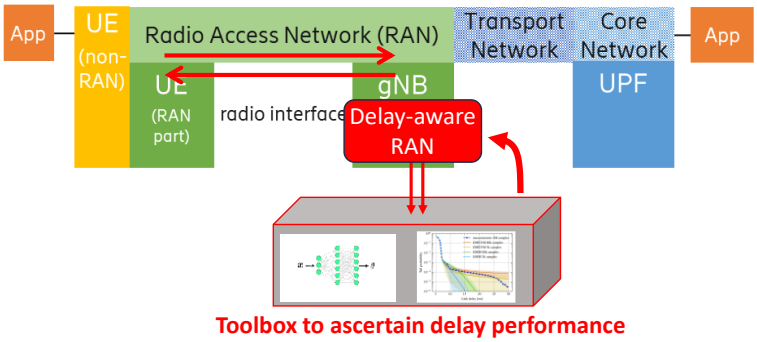


Figure 4-3: Design proposal for a delay-aware RAN architecture

4.2 Packet delay correction

An in-depth analysis of the multiple 5G components for packet delay and packet delay variation has been discussed. Even if the URLLC feature of 5G and further enhancements can lower the upper bound of packet delay, packet delay variation remains difficult to control. Indeed, packet delay variation is the most pronounced difference between e.g., wired TSN bridges and 5G logical TSN bridges.

Packet delay correction (PDC) was identified as a key mechanism to compensate for packet delay variation in the next generation 6G logical TSN bridges. Proposed approaches are intended to force all packet to spend the same or approximately (within a small range) the same delay within the 6G system (6GS) [DET23-D21] [DET25-D23]. That implies keeping packet delays towards the guaranteed upper bound that is guaranteed by the 6GS.

Different methods have been proposed and each with their strengths and weaknesses in terms of precision, its dependency with the type of traffic, the scope of application, and overhead generated by PDC metadata carried in every packet (see Table 2.1 in [DET25-D23]). The choice of the PDC to be implemented in the 5G/6G system needs to be matched with the E2E traffic requirements.

4.2.1 Timestamp-based PDC

An ingress point of a 6G logical TSN bridges (e.g., DS-TT or NW-TT) applies an ingress timestamp to packets belonging to the flow of interest (e.g., a TSN stream). This ingress timestamp travels with the packet as metadata to the egress point (e.g., NW-TT or DS-TT) where an egress timestamp is generated. The values of these two timestamps are used to calculate the residence time of the packet within the 6GS. Given a predefined maximum packet delay in the 6GS, PD_max, the packet is held at

the egress point for “PD_max - residence time” and then forwarded to the next hop after removing the ingress timestamp from the packet (see example in Figure 4-4). In this case, if all packets spend PD_max, then the PDV is zero. If instead of PD_max, a very small range of delay values is used, e.g., [PD_min, PD_max], then PDV becomes equal to this range. This solution requires time synchronization in both ingress and egress points.

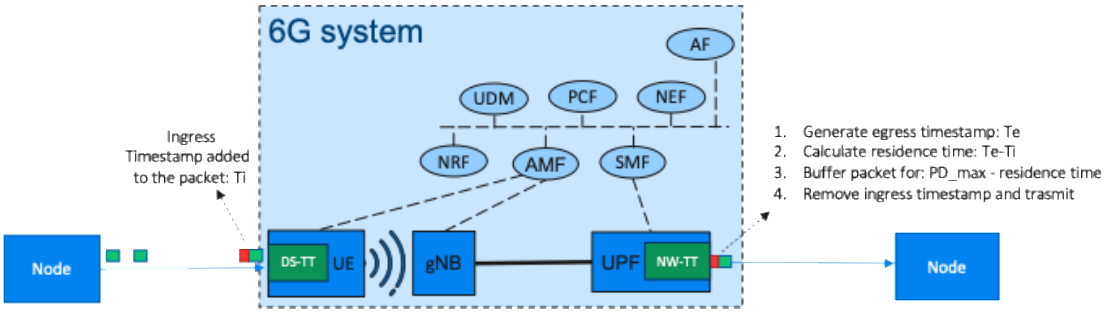


Figure 4-4: Illustration of the timestamp-based PDC

4.2.2 Virtual-timeslots-based PDC

This solution expands from the timestamp-based approach by using a predefined sequence number that states a new type of timestamp, namely the virtual timeslot. Instead of using an absolute time with high precision for the timestamping, the idea is to use a known timeslot size (i.e., not a single time value but a time range), whereby each timeslot is identified by an integer number, Slot ID. The ingress point inserts this integer value to the packet header, and the egress port calculates the egress timeslot at which the packet should be transmitted. It is calculated by adding the maximum predefined delay “target 6G delay” to the ingress Slot ID value carried in the packet (see example in Figure 4-5). The benefit here is that the metadata size requires less bytes and fast hardwire-speed timestamping is not required, which would imply a more costly interface at the ingress and egress points. This solution can provide a PDV that is in the order of the timeslot size.

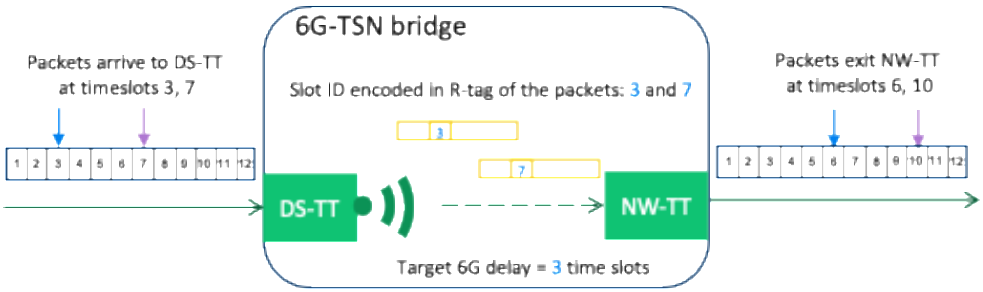


Figure 4-5: Example of timeslot-based PDC

4.2.3 Re-transmission-based

In this case the metadata in the packets will be the number of retransmissions for the data packet. The egress point, based on this information uses a Cyclic Queuing and Forwarding (CQF) system (see Figure 4-6) with an egress queue by considering the number of retransmissions. Packets are enqueued based on the retransmission number they carry as metadata, the actually served queue, and the CQF gate control list. The CQF that will cyclically select/serve the egress queue for transmission such that packets with larger number of retransmissions are transmitted earlier and packets with lower number

of retransmissions are transmitted later, achieving that the lower delay bound is pushed towards the upper bound. In other words, all packets will approximately be delayed the same time as the packets with largest retransmission number. The egress point in this case is placed after the air transmission and controls the lower bound of the packet delay distribution to become tighter toward the upper bound and thereby controlling the PDV introduced in the RAN segment which is caused by the Hybrid Automatic Repeat Request (HARQ) process.

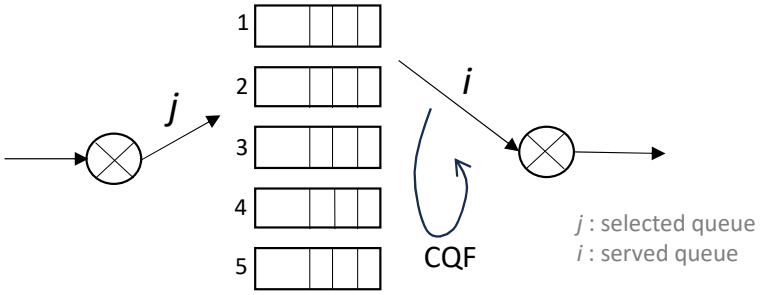


Figure 4-6: Queue selection in CQF

4.2.4 Periodicity-based PDC

This PDC for periodic traffic requires additional information. In particular, the value of the flow periodicity needs to be available at the egress point. The essence of this approach is to calculate the forwarding time of a packet n by simply adding the period value to the forwarding time (FT) of the previous packet (n-1) belonging to the same queue. The egress point keeps track of the last forwarding time, and if it knows the value of the flow period, then the egress point can also calculate the forwarding time of the next packet (as shown in Figure 4-7).

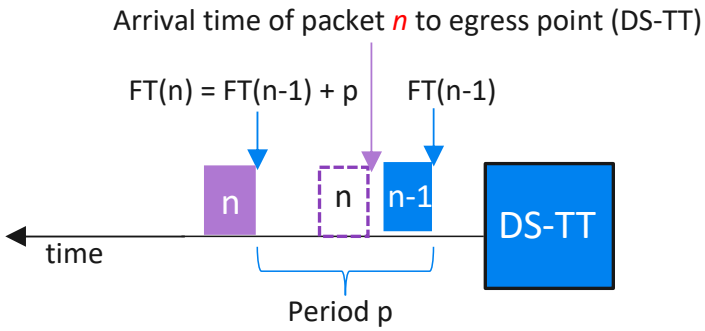


Figure 4-7: PDC method for periodic traffic and its application at the egress point (example DS-TT)
FT(n): forwarding time for packet n (for integer n>0)

4.2.5 PDC E2E validations

Evaluations have been performed to evaluate timestamp-based and virtual-timeslot-based PDCs [DET25-D23]. It was shown that the TSN 802.1Qbv scheduled traffic will perform very poorly when any (virtual) node introduces significant PDV: streams' deadlines cannot be fulfilled. The reason is that the TSN scheduler considers the worst case 6G-delay in order to make its per-node scheduling calculations. It was noted that large PDV can lead to uncertain enqueueing where packets from different TSN streams are enqueued in an unexpected order (as per TSN scheduler calculations). This leads to a number of packets, that should have been enqueued earlier than other packets, to be postponed for the next 802.1Qbv hypercycle and consequently missing their deadline. On the other

hand, when 802.1Qbv scheduled traffic is used in conjunction with a PDC method such as the timestamp-based PDC, then the delivery is just as expected and on-time since there is no overflow of packets to subsequent 802.1Qbv hypercycles. Additionally virtual-timeslot-based PDC is evaluated, and its impact is reflected in a reduced number of streams that can be scheduled without incurring in the issue of uncertain enqueueing, as shown in Figure 4-8.

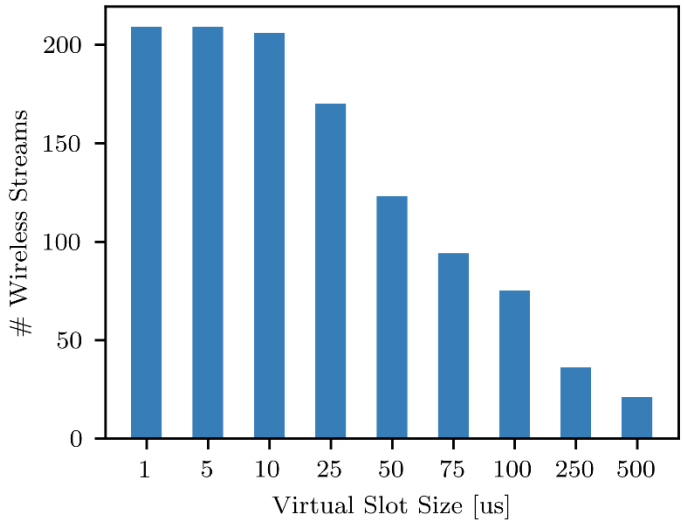


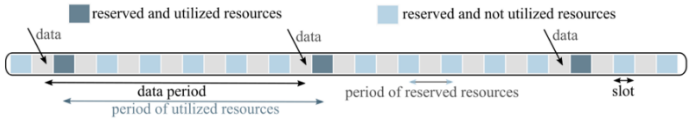
Figure 4-8: Effects of the virtual timeslot granularity on schedulability

4.3 RAN resource management

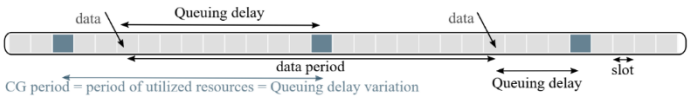
RAN scheduling strategies are another important enabler for time-critical and dependable 6G services. We introduce two main solutions with different targets [DET25-D23]. Firstly, we propose for application's traffic pattern alignment for the optimization of RAN scheduling to achieve lower packet delay. Secondly, a novel reinforcement-learning-based RAN scheduling strategy is proposed to improve availability and reliability considering environmental information.

4.3.1 Application's traffic pattern alignment for the optimization of RAN scheduling

The target of this solution is the queuing packet delay (PD) in cellular communications, originating from a misalignment of periodic traffic arrival time instances and the scheduled reserved resources, which results in significant PDV. Figure 4-9 illustrates the tradeoff between the resource overprovisioning vs. high PDV, in case of no alignment between the reserved RAN resources and the data arrival, while Figure 4-10 presents the case where an ideal time-alignment is achieved. It is important to note that standardization support for periodic deterministic communication in the context of alignment of the traffic sending time with the scheduled resources in the 5G-TSN system was highlighted. However, the challenges and missing interfaces were discovered and enhancements for resource optimization to increase the traffic capacity with decreased PD and PDV were proposed in the project. We outlined the E2E flow of the *time sensitive communication assistance information* (TSCAI) parameters from applications, via TSN network to the RAN within the 6GS, and the flow of the RAN feedback in the opposite direction. Finally, we presented the improvements of the PD and PDV, based on measurement and simulation results across various scenarios in case the TSCAI, RAN Feedback and stream information parameters are used.



(a) Overprovisioning of resources with low PD and PDV



(b) No overprovisioning, high PDV

Figure 4-9: Trade-off between resource utilization and PDV

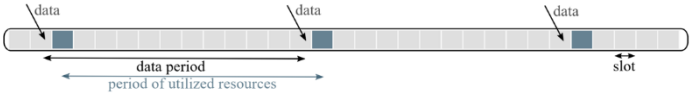


Figure 4-10: Ideal use case with time-aligned reserved resources and the data arrival

4.3.2 Dependable 6G using environmental-aware reinforcement learning-based scheduling strategy

This reinforcement-learning-based (RL-based), environmental-aware scheduling strategy enhances the defined dependability aspects by leveraging real-world network conditions to optimize reliability, availability, and fairness in dynamic environments. Unlike traditional schedulers that focus solely on network performance indicators (NPIs) like throughput and delay, this approach integrates environmental awareness to make intelligent scheduling decisions based on real-time conditions such as LOS/NLOS states. By using a Deep Q-Network (DQN), the scheduler learns to balance competing objectives, ensuring stable and continuous service even in challenging, high-obstruction environments. The methodology of the proposed scheduling strategy is illustrated in Figure 4-11.

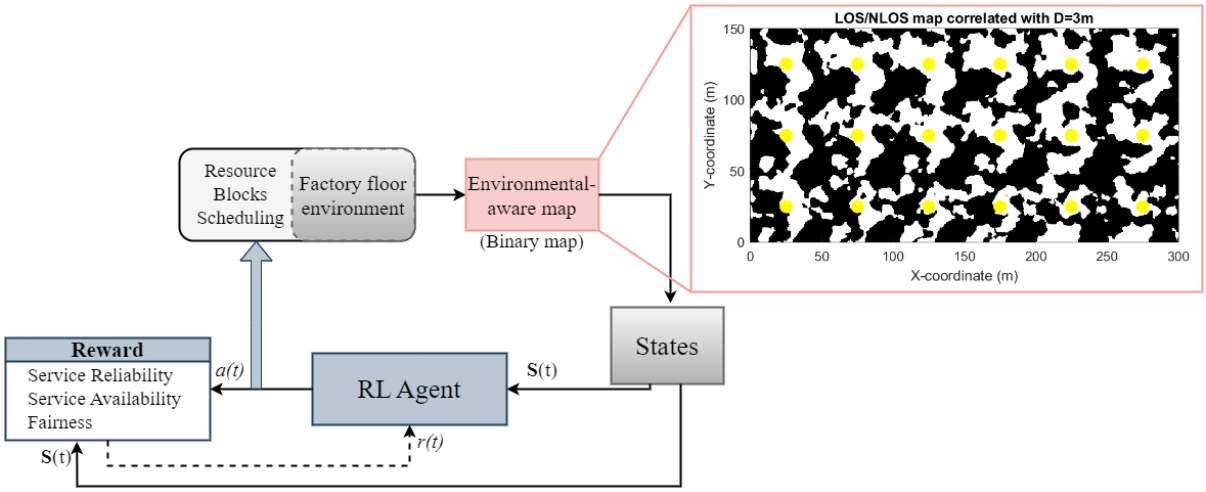


Figure 4-11: Methodology of the environmental-aware RL-based scheduler

The results show that this method significantly outperforms classical scheduling strategies, particularly in scenarios with high clutter density where changes from LOS to NLOS are very frequent, demonstrating its potential for future 6G deployments where dependability is critical.

4.4 Time synchronization

Time synchronization remains a key enabler to not only support internal 5G/6G functionality, but also to deliver time-critical and dependable services. Indeed, it is needed for observability and to be able to extract the information needed to perform data-driven analysis and predictions. Time synchronization is also needed for minimizing PDV via packet delay correction mechanisms.

4.4.1 Reliability of time-aware systems

A time synchronization service is available in 5G since Release 16, however, time synchronization reliability remains an important issue. Indeed, there is a need to support resilient time synchronization mechanisms in time critical 6G-TSN applications in order to meet high levels of availability for the time synchronization service. The current TSN time synchronization (generic Precision Time Protocol (gPTP), IEEE 802.1AS) relies on the Best timeTransmitter Clock Algorithm (BTCA) to find the next grandmaster (GM) clock, when the current GM clock has failed or degraded in performance. However, BTCA may take time to find the next GM. Additionally, BTCA is unable to detect transient faults in a GM, hence could lead to a ping-pong effect between two potential GMs. For the emerging 6G-TSN use cases, this waiting time without a time synchronization source is not desirable. With the objective to provide a continuous precise timing, the new amendment of the IEEE 802.1AS standard (802.1ASdm) provides the hot standby mechanism. Here BTCA is disabled and instead a static configuration is sent down from the network management system (e.g., the Centralized Network Controller (CNC) in the case of TSN).

From an architecture point of view [DET23-D22] analyses the different implications on the location options of the GM, the redundancy design, and the 3GPP support for such a scenario. Indeed, the location of the primary and hot standby GM will determine the coverage of synchronization redundancy. Hence, a careful design to optimize the location of such GM clocks is required. More importantly is the aspect of 3GPP support of the 802.1ASdm amendment, and consequences based on whether the 6G GM becomes the primary GM or the hot standby GM. Figure 4-12 presents possible placement of the primary and hot standby GM in a 6G-TSN network.

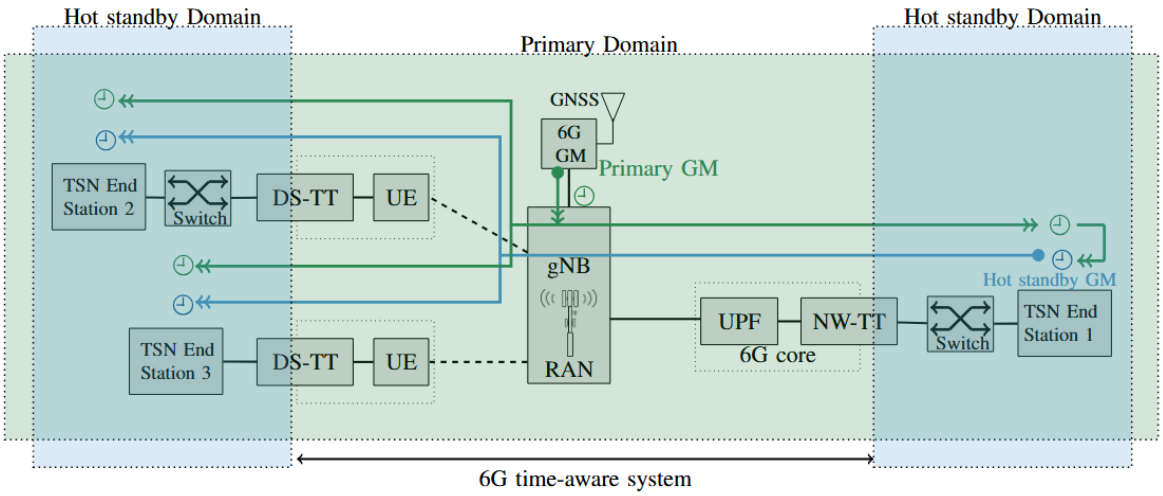


Figure 4-12: 6G as primary GM and network side TSN end station as hot standby GM.

4.4.2 Analysis of time synchronization architectures with hot standby

The scenarios with a hot standby GM outperform BTCA in terms of clock drift and out-of-sync time in case of failures. However, our analysis indicates that in certain failure cases, parts of the network may be left without a GM when using static GM configuration (hot standby). In contrast, BTCA is able to dynamically select a new GM in the event of failure, albeit with some delay. This leads us to conclude that the decision to use a static GM configuration with hot standby or a dynamic GM configuration with BTCA should be based on the network topology and the presence of other redundancy measures, such as link redundancy. For instance, in a network with multiple redundant links, a static GM configuration with hot standby might be more effective. Conversely, in a network with fewer redundancy measures, a dynamic GM configuration could provide better resilience by dynamically selecting new GM in case of failure.

Figure 4-13 presents the simulation scenario analyzed for the comparison of BTCA and hot standby system [DET25-D24].

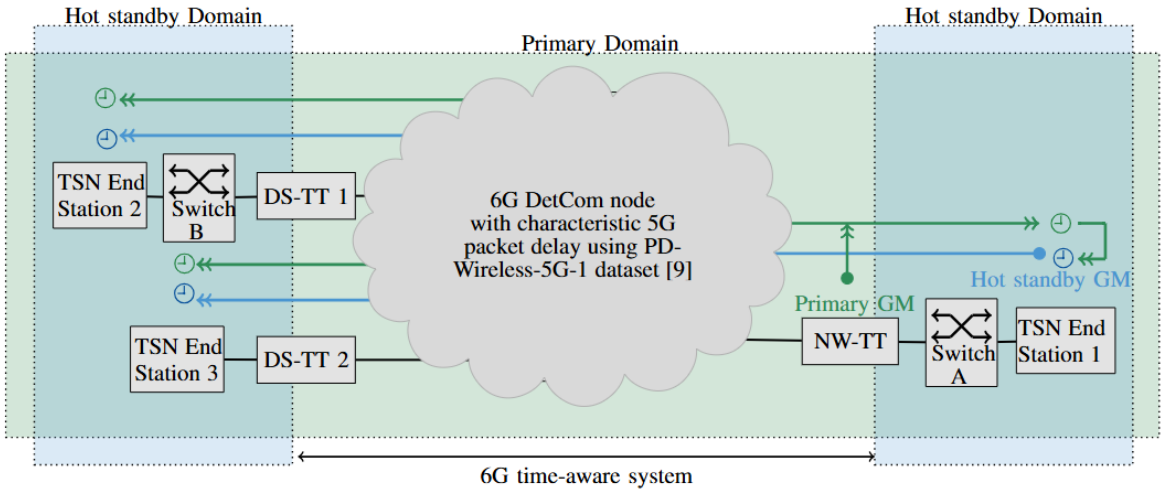


Figure 4-13: Hot standby scenario with 6G system transmission delay modelled using measurement data sets from real-world 5G testbeds

4.4.3 Security for time synchronization in 6G

Mechanisms to improve security of time synchronization messages were also proposed. Specifically, different attack vectors on time synchronization mechanisms were identified, and also mitigation techniques were provided [DET23-D22] [DET25-D24].

Although Annex P of IEEE 1588-2019, also known as Profile D, has introduced several security features to protect clock synchronization to deal with attacks such as spoofing and message tampering, interruption of message exchange, and replay of messages, these mechanisms remain ineffective against Time-Delay Attacks (TDA). Unlike traditional cyberattacks that alter packet content, a TDA does not manipulate PTP messages but only delays the packet, for example, an attacker intercepts a PTP message and holds it for a given interval before relaying it to its destination. The attacker can use various delay attack strategies such as maliciously added delay can be constant, jittered, or slowly wandering.

4.4.4 Emulation framework to evaluate monitoring of time-delay attacks

As TDA can be detected only via monitoring, we propose to use In-band Network Telemetry (INT) to monitor PTP frames in real time. The INT metadata are embedded inside Type-Length-Value (TLV) extensions of PTP frames. This integration does not cause any incompatibility in the network devices, such as PTP server or client. Using PTPv2 extensions for INT has significant advantages, as it allows for high-precision latency measurements, real-time network optimization, and proactive security monitoring, such as detecting time-delay attacks on PTP synchronization [DET25-D24]. In Figure 4-14 the pernicious Time Delay Attack (TDA) can be detected by monitoring the Inter Arrival Time (IAT) between synchronization messages and detecting changes (i.e., IAT variations).

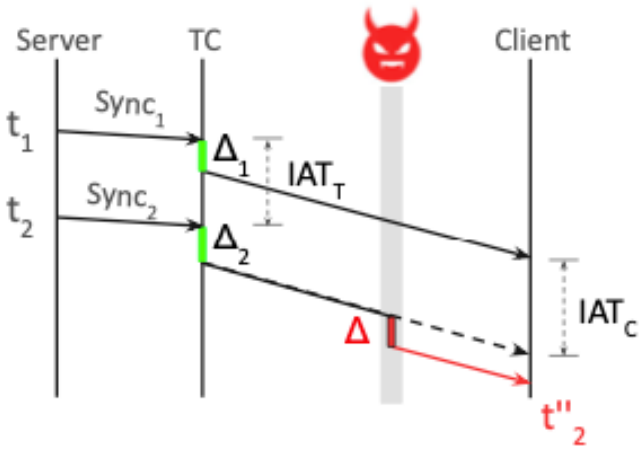


Figure 4-14: Detection of TDA via IAT Variation in E2E Time synchronization

To evaluate the proposed approach, we implemented an open-source emulation to emulate precision time synchronization and to perform TDA attack & detection. The programmable Transparent Clock is implemented using P4 and it can be enabled or disabled its INT capability at runtime to encapsulate monitoring data into PTP frames. Experimental evaluations demonstrated that our P4-based transparent clocks achieve accuracy comparable to LinuxPTP-based implementations, with clock offset values remaining below 200 µs. The security framework we designed includes a learning phase

to establish a detection threshold, ensuring that anomalies in synchronization performance trigger alerts only when deviations exceed expected accuracy.

This work contributes toward integrating time synchronization into software-defined networking (SDN) and network programmability, paving the way for more secure and flexible synchronization mechanisms.

4.5 Key takeaways

Several 6G-centric enablers have been proposed and validated. Firstly, PDV can be minimized via the use of packet delay correction mechanisms applied at the edges of the 6G system. Secondly, packet delay can be analyzed and predicted via data-driven characterization approaches that enable network adaptation and dependability. Thirdly, packet delay and availability of the 6G service can be controlled via RAN resource allocation mechanisms proposed in this project. Finally, time synchronization is key to support all previous approaches, and the aim here has been towards a more reliable and secure time synchronization service.

5 Enablers for 6G convergence with dependable, time-critical communication

The seamless integration of 6G as part of end-to-end deterministic communications requires the analysis of different frameworks, such as TSN and DetNet. DETERMINISTIC6G investigated the impact of 6G wireless transmission and explored how to enable resource-efficient and optimized end-to-end communication for deterministic communication services. As part of the convergence of 6G into dependable and time-critical communications, new concepts and algorithms for calculating global deterministic end-to-end schedules were proposed, considering the stochastic characteristics of 6G logical TSN bridges.

First, a model for extending the current TSN control plane was considered to introduce the concept of dynamic behavior of 6G wireless systems. This model should provide the CNC the required information for calculating a global schedule that considers the expected delay and delay variation of a 6G logical TSN bridge.

DETERMINISTIC6G reviewed the existing edge computing systems that can host applications requiring substantial computation and identified a set of improvements that are necessary to guarantee dependable, time-critical, and deterministic communication performance. In DETERMINISTIC6G we concluded that the edge computing domain needs to incorporate features of Time Sensitive Networking (TSN) and Deterministic Networking (DetNet).

In DETERMINISTIC6G we also analyzed different techniques for non-disruptive monitoring, which is a passive monitoring solution. The objective was to validate a security solution that does not introduce additional latency into network traffic. In the project we considered a monitoring solution that was deployed by capturing network packets at a given observation point to provide information on the current network status. Another option consisted of introducing some telemetry on the packets which adds extra latency on the packets. A prototype was implemented for demonstrating that this option is a helpful tool for identifying security issues as it can provide historical information of a packet via the INT metadata added to the packet by switches/routers the packet passes through.

Furthermore, predicting the behavior of physical systems and processes while generating various alternative scenarios can further enhance the end-to-end time-aware communication system. This work was carried out as part of the Digital Twin (DT) design.

5.1 Extension of TSN control plane model: Concept for modeling dynamic system behavior

Logical (wireless 5G/6G) TSN bridges show a significantly different, characteristic port-to-port delay compared to wireline TSN bridges, with larger port-to-port delay (several milli-seconds vs. several micro-seconds), larger delay variation, and heavy-tailed delay distribution. Moreover, the delay distribution might change dynamically over time depending on 5G/6G network conditions. Our algorithms to calculate wireless-aware end-to-end schedules (see Section 5.2) exploit knowledge of the stochastic port-to-delay distribution, to enable stochastic end-to-end delay guarantees and efficient resource utilization with respect to the number of streams than can be admitted to the network.

To enable such novel wireless-aware scheduling approaches, we have proposed extensions to the TSN network control plane to provide information about the port-to-port delay of bridges as measured online or predicted to the Centralized Network Controller (CNC) executing the algorithms to calculate schedules (see Figure 5-1). Our extensions are based on standard protocols and modeling concepts, namely NETCONF for the communication of delay information between logical bridge and CNC, and YANG models to describe delay distributions.

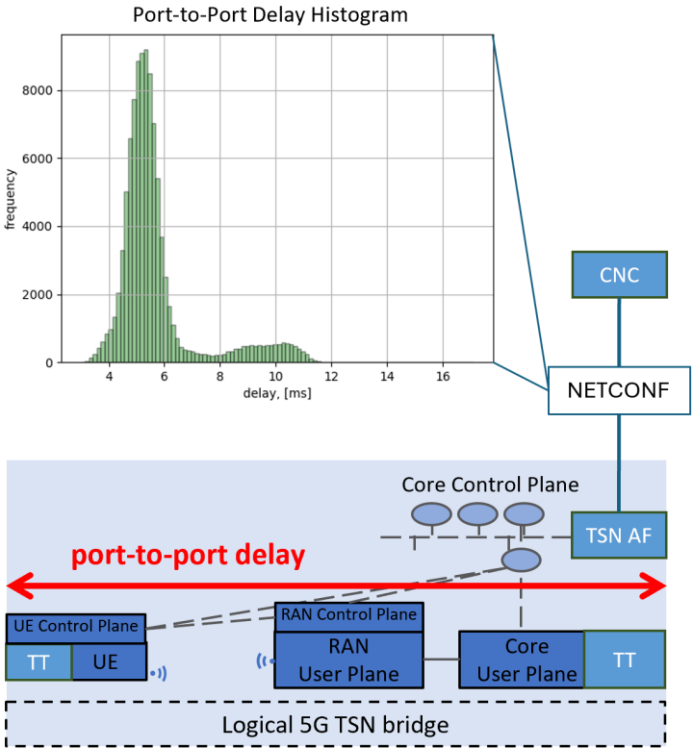


Figure 5-1: Extended TSN control plane for communicating port-to-port delay histograms between logical 5G TSN bridge and CNC via NETCONF

The first main contribution is a YANG model for describing port-to-port delay distributions of TSN bridges as histograms, rather than the conservative minimum and maximum delay bounds defined in

the TSN standard IEEE 802.1Qcc [IEEE18-8021Qcc]. Individual histograms can be defined per port pair and traffic class. The main features of our modeling approach are:

- Fine-grained modelling of stochastic delay distributions. The granularity of the model can be adjusted and is sufficiently flexible to define probabilistic bounds (probability of delay values within a delay interval) as well as the classic worst-case deterministic bounds (min-max interval with 100 % probability) from IEEE Std 802.1Qcc [IEEE18-8021Qcc].
- Independent and dependent delay distributions: Delay can be defined as independent, i.e., applying to all possible states. We also support a generic notion of dependent delays that are only applicable in certain states. The actual definition of "states" is deliberately kept generic such that delay distributions could depend on any relevant state. For instance, we could define different distributions for different frame sizes (frame length dependency), different physical speeds of end stations (mobility dependency), etc. Important for our algorithms for proactive schedule adaptation is mainly that we can calculate schedules for different possible future states proactively, and then switch to the corresponding schedule when the state occurs.
- Validity period: Dynamic packet delay information might only be valid in a certain time frame or up to a certain time horizon. Therefore, we add the capability to optionally specify a period of validity.

A detailed definition of the model schema can be found in Deliverable D3.4 [DET24-D34].

Secondly, we have shown how to support the reactive ("break-before-make") and proactive ("make-before-break") adaptation of schedules using standard NETCONF mechanisms to update dynamic port-to-port delay distributions, which might change over time depending on the network state. Proactive schedule adaptation takes advantage of latency prediction concepts at logical bridges (see Section 4.1.3) to inform the CNC of new delay distributions before the old end-to-end schedule becomes invalid. This provides the CNC with sufficient time to perform the complex task of re-calculating schedules.

On the one hand, our approach supports polling of delay distributions through NETCONF get requests. For proactive adaptation of schedules, polling can also be triggered before the old schedule becomes invalid if it is known, when the current delay distribution will expire as defined by the validity period attribute of the model.

On the other hand, our approach support utilizing the NETCONF event mechanism (on-change subscriptions in YANG Push). The idea is that the logical bridge informs the CNC if the current distribution deviates from the old distribution significantly, justifying an adaptation of the end-to-end schedule.

A more detailed description of these NETCONF-based polling and event-driven mechanisms is also presented in Deliverable D3.4 [DET24-D34].

5.2 Wireless-aware design of end-to-end dependable, time-critical communication

The calculation of IEEE 802.1Qbv schedules for wired TSN networks has received considerable attention (see [SOL+23] for an overview of existing approaches). Therefore, it is tempting to re-use these "wireless-unaware" algorithms in networks with wireless bridges. However, this will lead to fundamental challenges as discussed below.

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

As an alternative to the usage of dedicated hold-back buffers of PDC in Section 4.2, a wireless-aware scheduler can configure the IEEE 802.1Qbv schedule to compensate for a bounded packet delay variation [dmin , dmax], as perceived in a logical 5G/6G-TSN bridge. It requires that the scheduler (i.e., the CNC) is provided with some statistical knowledge about the 5G/6G packet delays, which can be provided for instance in the form of an empirical histogram. A robust IEEE 802.1Qbv schedule must provide formal end-to-end QoS guarantees for frames whose 5G/6G delays are bounded by [dmin , dmax]. Importantly, these guarantees are made for each individual TSN stream, i.e., transmission faults of one stream must not impair the QoS guarantees of other streams. Moreover, leaving the wireless-aware scheduler to influence the 5G/6G packet delay budgets [dmin , dmax] has two main advantages:

1. Instead of having to compensate for the maximum PDV, the scheduler can choose a sufficiently large packet delay budget to satisfy the stream's reliability requirement.
2. In case of a significant disruption in the 5G/6G channel conditions, a wireless-aware scheduler can realize graceful degradation in the streams' latency and reliability guarantees, instead of having to drop individual streams entirely.

Striving towards this goal, it is also necessary to address the problem of low schedulability with conventional IEEE 802.1Qbv scheduling approaches. To this end, we introduced the concept of controlled frame interleaving approach: Intuitively, controlled frame interleaving moves away from the conventional approach to exclusively reserve transmission slots for individual frames. Instead, it enables wireless streams to share the same transmission slot by creating frame batches. While allowing frame re-ordering within the same batch to improve link utilization, streams are only allowed to interleave if the streams' latency guarantees can be satisfied (i.e., each frame arrives before its deadline even when being the last one in its batch). Figure 5-2 shows one example of a comparison of our Full Interleaving Packet Scheduler (FIPS) vs. Strict Transmission Isolation (STI) using scheduling with exclusive timeslots per frame as known from existing wireline TSN networks. This result clearly shows that FIPS is able to schedule substantially more streams for different target levels of reliability (maximum allowed fraction of deadline violations) than STI. For further details, we refer the interested reader to [EGS+25].

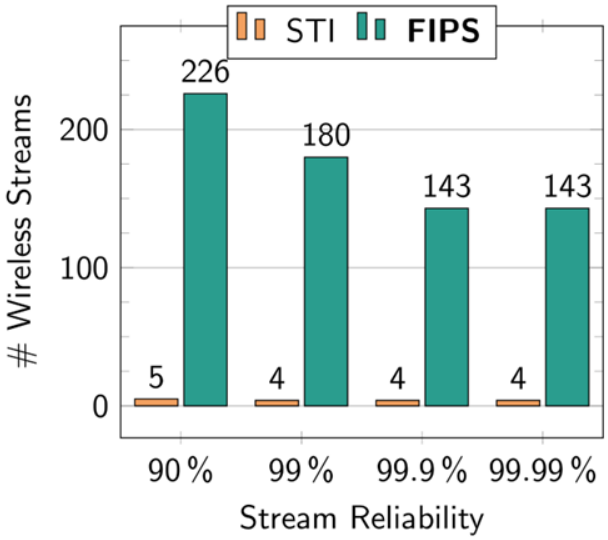


Figure 5-2: Scalability of our FIPS approach vs. classic scheduling (STI)

5.3 Edge computing solutions for supporting deterministic services

Edge computing architecture as defined in standards requires additional functionality for supporting deterministic services. The edge domain data plane requires the development of new concepts and to investigate the features in the direction of 6G convergence with deterministic communication requirements. The results of the edge cloud solutions for deterministic communication service are presented in this section. The main architectural options for integration of cloud and 6G deterministic communication networks, reliability and timeliness traffic handling for the cloud domain, control plane interworking are addressed.

5.3.1 MEC

The edge computing was analyzed from different deployment scenarios to identify the features required to support deterministic communications. Thus, standalone and operator-enabled scenarios were considered; detailed analysis can be found in Deliverable D3.3 [DET24-D33] and Deliverable D3.6 [DET25-D36].

Standalone Edge scenario

In a standalone edge deployment, a standalone datacenter infrastructure is deployed to host the cloudified applications (also referred as TSN Talkers/Listeners). This approach provides more flexibility with more distributed infrastructure for ensuring high reliability, customized traffic handling, and tight interworking with the TSN domain as shown in Figure 5-3.

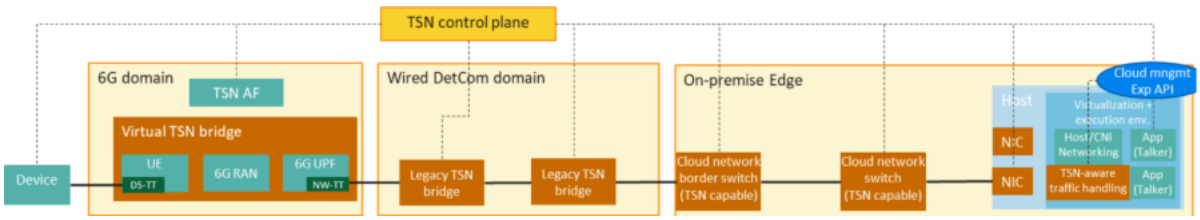


Figure 5-3: Standalone edge deployment

The TSN control plane can obtain all the required information on the topology and the capabilities of the switches, and the edge host capabilities can also be obtained. Based on these capabilities, the traffic schedule parameters can be configured in all devices, in an end-to-end manner. The obvious advantage of this option is that all the TSN features (e.g., TSN 802.1Qbv – scheduled traffic, or TSN 802.1CB – Frame Replication and Elimination for Reliability) can be fully utilized in the cloud domain.

Operator enabled scenario

In this setup as illustrated in Figure 5-4, the 6G network operator owns or operates the edge cloud domain as well, enabling a tighter integration of this domain. In this scenario the components of the 6G network can be deployed within the edge cloud domain.

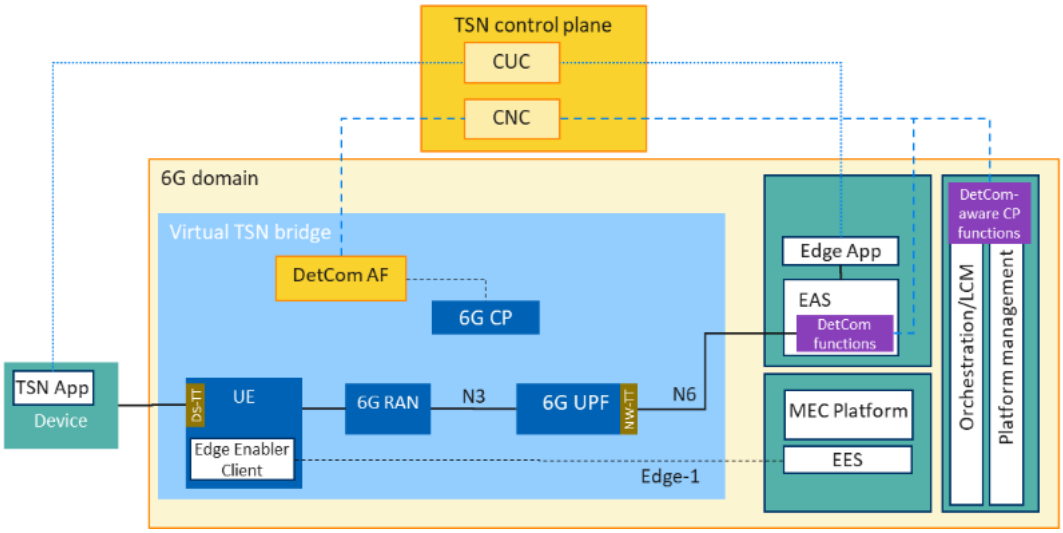


Figure 5-4: Operator enabled Edge

For a TSN (client) App on the device to utilize functionality provided by another TSN (server) App deployed in the cloud, the application deployment, service initiation and service configuration steps are needed – detailed description of these steps can be found in [DET25-D36].

5.3.2 Integration aspects of Edge computing and TSN for seamless support of IEEE 802.1Qbv scheduling for cloudified applications

For the efficient end-to-end support of IEEE 802.1Qbv traffic scheduling for cloudified applications, a framework was developed, that combines a) the proper configuration of the cloud execution environment to ensure time-bounded execution of specific application instances and b) traffic handling methods in the virtualized networking domain of a cloud host, capable to mimic the seamless 802-1Q-aware scheduling.

To guarantee time-bounded execution Deliverable D3.3 [DET24-D33] summarizes the enablers that can be leveraged for supporting the time-bounded execution of time-critical applications. These include the coordinated use of orchestration, proper resource isolation and allocation, CPU scheduling, and real-time capabilities of the virtualized environment.

As the essence of seamlessly supporting 802.1Qbv scheduling is to ensure that packets arrive at the NIC according to the scheduling plan designed by the TSN control plane (CNC), a framework was

developed (details can be found in D3.3 [DET24-D33]) that includes time-bounded application execution using deadline scheduling (SCHED_DEADLINE[2]) for all the time-critical applications. To guarantee the proper timing and ordering of packet arrival at the NIC, the other component of the framework is a Time-Aware Priority Shaper (TAPRIO[3]) - based traffic handling scheme, whose configuration is derived from the 802.1Qbv scheduling plan. For the containerized environment, two alternative traffic handling approaches have been developed:

- Coordinated gating mechanism: In this option, TAPRIO is configured on the virtual Ethernet interfaces of the containers hosting time-critical applications in a coordinated manner, ensuring that at any given time, only a single container is allowed to send traffic towards the NIC.
- Centralized traffic scheduling mechanism: In this option, an Open vSwitch (OVS) Kubernetes Container Network Interface plugin (CNI) is used, and the TAPRIO-based scheduling scheme is configured on the egress interface of the OVS, which is connected to the NIC. The method includes a classifier, combined with priority queuing or Cyclic-Queuing and Forwarding (CQF) to ensure the correct ordering of packets, and the TAPRIO configuration is used to control the forwarding time of specific packets towards the hardware queue of the NIC.

The operation of the methods is verified by simulations, as summarized in D3.3 and D4.5 [DET25-D45].

In D3.6 [DET25-D36] another approach was developed, leveraging tight integration with the Kubernetes cluster networking. The scheduling information is propagated with eBPF[4] as a metadata for each packet, and a TSN proxy – implemented as a secondary Kubernetes CNI plugin – is used for handling the propagation of TSN scheduling information. Measurement results for this method are also included in D3.6 and D4.5.

Even though several enablers to ensure time guarantees are used, the cloud execution environment remains a stochastic system. To expose the capabilities and uncertainties, which must be considered in the construction of end-to-end 802.1Qbv scheduling, a proposal for an abstract representation of a cloud host is introduced in D3.6. This abstraction is capable of describing the characteristics of arbitrary cloud host according to the IEEE 802.1Qcc and IEEE 802.1Qdj standards. Its essence is to represent the cloud host and application deployment as a combination of virtual TSN endpoint and bridges, as illustrated in Figure 5-5.

[2] https://docs.kernel.org/scheduler/sched-deadline.html
[3] https://man7.org/linux/man-pages/man8/tc-taprio.8.html
[4] https://ebpf.io/

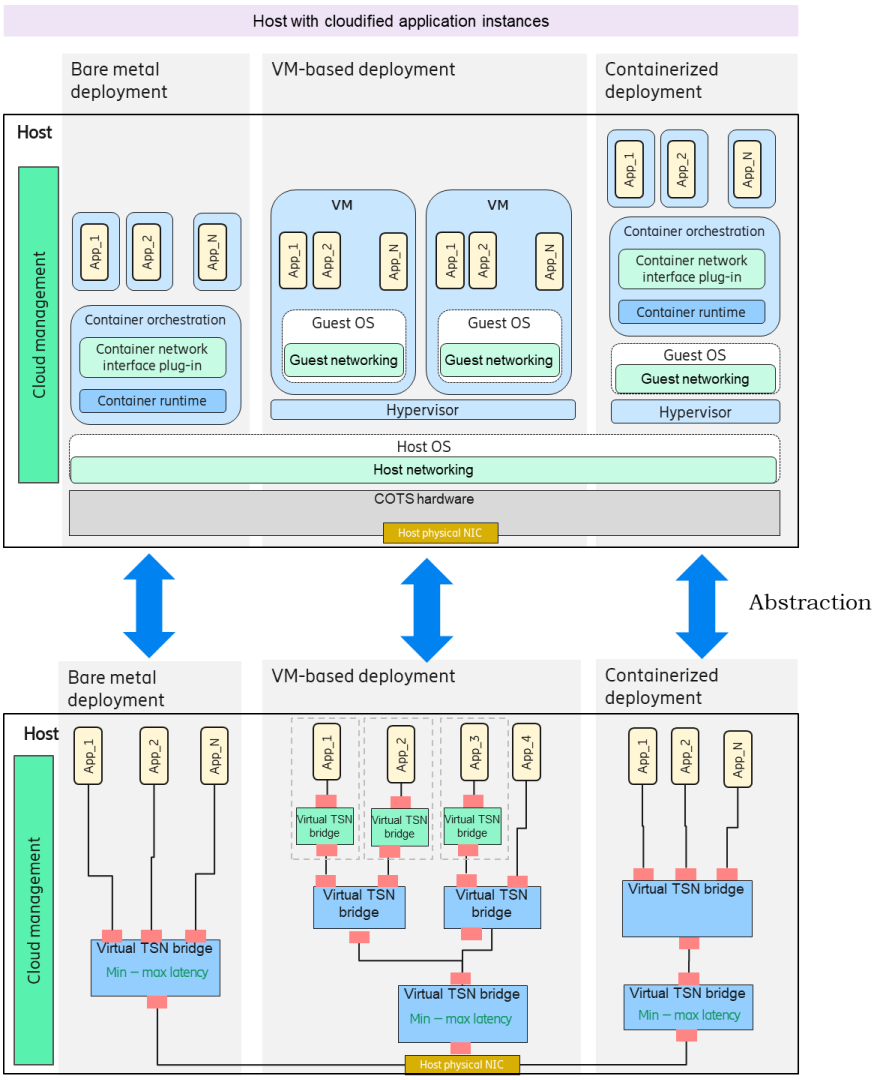


Figure 5-5: Abstraction of cloud host with various virtualization deployment options

The App instances in Figure 5-5 – considered as virtual TSN endpoints – and their connections to virtual TSN bridges represent the application scheduling (timing) capabilities provided by the underlying cloud execution environment (e.g., how CPU resources can be reserved for executing a specific application instance). The virtual bridges (blue entities in Figure 5-5) represent the characteristics of host's virtualized networking, depending on the cloud deployment options. A *TSN-aware cloud management entity* is also described, which is responsible for *a)* exploring the cloud host and collecting the capabilities of the current deployment, *b)* constructing and parameterizing the abstracted view for the TSN control plane, as well as *c)* initiating the configuration of the cloud deployment-specific 802.1Qbv-aware traffic handling scheme.

5.4 Security by design architecture and framework

In the DETERMINISTIC6G project, the security-by-design task focuses on specifying and designing a comprehensive end-to-end (E2E) security architecture and framework for deterministic networking in virtualized and edge-based heterogeneous networking environments. Specifically, in Deliverable D1.2 [DET24-D12], we provided a comprehensive overview of potential threats to the deterministic properties of networks and presented a range of remediation strategies to prevent, detect, and

mitigate those threats. In Deliverable D2.2 [DET23-D22], we focused specifically on how these threats affect time synchronization protocols, summarizing the threat model and its impact on time-aware networks.

While cryptographic solutions, such as E2E encryption, are effective in protecting against many threats like message tampering, spoofing, packet replay, and communication disruption, they fall short when it comes to delay-based attacks. These include Denial-of-Service (DoS) attacks or insider threats where the attacker has access to a trusted part of the network or possesses encryption or authentication keys. A notable example is the Time-Delay Attack (TDA). Unlike conventional cyberattacks that alter packet contents, a TDA works by delaying a Precision Time Protocol (PTP) packet without modifying it. An attacker may intercept a synchronization message, hold it for a brief period, and then forward it to its destination. This intentional delay skews propagation delay measurements, causing synchronization errors across downstream clocks.

Detecting TDAs is especially challenging because their behavior closely mimics normal network latency, leaving no obvious signs like those found in traditional attacks. By subtly manipulating packet delivery timing, these attacks can bypass standard cryptographic defenses. This highlights the need for continuous monitoring of timing patterns to identify deviations before they impact system integrity. To effectively counter such threats, detection and prevention mechanisms must be able to identify timing anomalies quickly. Intrusion Detection Systems (IDS) tailored for deterministic networks should not only detect malicious activity but also monitor the timing and sequencing of packet arrivals to spot irregularities. In these environments, where precise timing is critical, anomaly detection must extend beyond payload inspection to include behavioral analysis of time-sensitive flows.

To address this gap, a security-by-design approach was introduced in Deliverable D3.2 [DET23-D32]. This approach integrates high-precision telemetry with a programmable data plane to enhance security management in deterministic networks, providing the visibility and control needed to detect and respond to subtle timing-based attacks. To ensure a self-contained explanation, we provide a summary of this approach below.

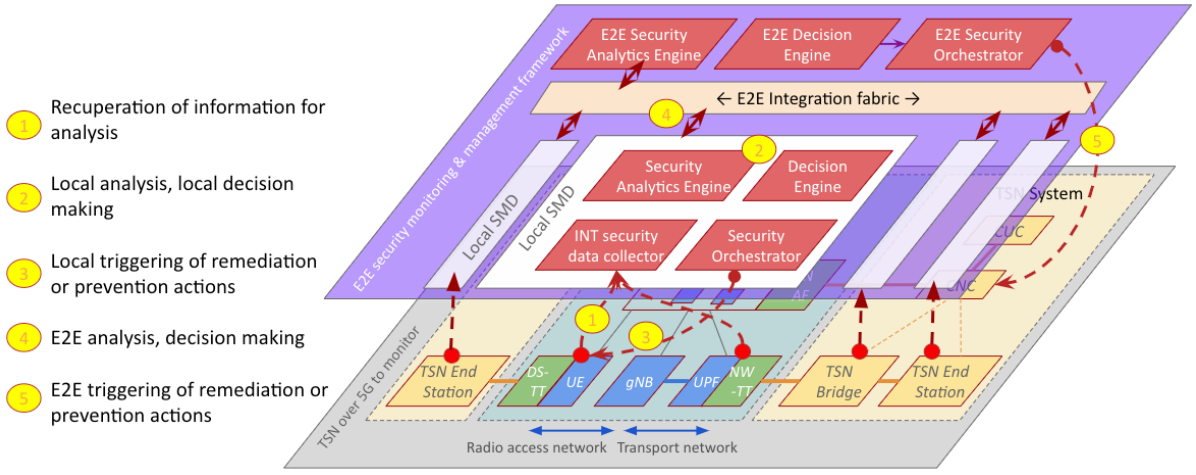


Figure 5-6: High level architecture of E2E security monitoring & management framework

Figure 5-6 illustrates a deployment architecture for security and enforcement services, incorporating High-Level Architecture (HLA) functional blocks and services. This architecture is designed not only to

enhance security but also to foster trustworthiness and accountability in the management of 5G/6G network infrastructures across multiple domains. Within the DETERMINISTIC6G project, the architecture is being extended to more comprehensively address the requirements of deterministic networking. This enhancement includes the integration of high-precision monitoring techniques and the support for both Time-Sensitive Networking (TSN) and Deterministic Networking (DetNet) domains. The goal is to establish a robust, efficient framework capable of meeting the stringent demands for precision, reliability, and consistency that are fundamental to deterministic communication environments.

The architecture is organized into multiple Security Management Domains (SMDs), each designed to ensure system resilience and to separate concerns across different parts of the network, such as the Radio Access Network (RAN), Edge, and Core Network. Each SMD is responsible for intelligent, AI-driven security automation within its domain and includes a set of functional modules, including the Security Data Collector, Security Analytics Engine, Decision Engine, Security Orchestration, and others. These modules collectively deliver a wide range of security services, accessible both within their respective domains and across domains via an integration fabric.

A specialized domain, known as the E2E SMD, is dedicated to managing the security of E2E services. By decoupling E2E security management from domain-specific SMDs, the architecture avoids monolithic designs, reduces complexity, and supports independent evolution of security mechanisms both at the domain and cross-domain levels.

All functional modules operate in an intelligent closed-loop cycle, consisting of data collection, threat detection, and response (as outlined in Steps 1 to 5 of Figure 5-6). This enables AI-driven, software-defined security (SD-SEC) orchestration and management, aligned with Security Service Level Agreements (SSLAs) and regulatory compliance requirements.

5.5 Situational awareness via digital twinning

In recent years, the concept of network digital twins (DT) has received increasing attention from the research community in the context of mobile networks like 5G but also for upcoming 6G systems. Network DTs comprise information about devices and traffic flows, network load, network connectivity characteristics, and other network parameters. Such state information is fed to the DT continuously either through collecting the information from the network or through explicit services, for instance, with respect to the sensing functionality of devices. While DTs have arguably existed already for a long time in networked systems, for instance as an information base to run a network operation center, network DTs are recently recognized as a valuable asset for application layer services, as well as for Artificial Intelligence (AI)-implementations targeting ultimately network (and application) optimization.

To improve the resilience of the 6GS and factory operations, we proposed in Deliverable D3.3 [DET24-D33] the use of DTs for both OT and 6G systems, not only for individual optimizations within their respective domains but also for interactive coordination to gain and utilize Situational Awareness (SA) on both sides, as illustrated in Figure 5-7. In an industrial scenario, these two systems are not independent from an operational standpoint. Operational changes in the manufacturing process in a factory will affect the network and vice versa. For this reason, we proposed allowing active interactions between the systems, which enables joint planning and execution of new tasks. We suggested that such novel interactions are raised to the DT level, where every task could be evaluated in many different scenarios and configuration options without affecting the ongoing processes.

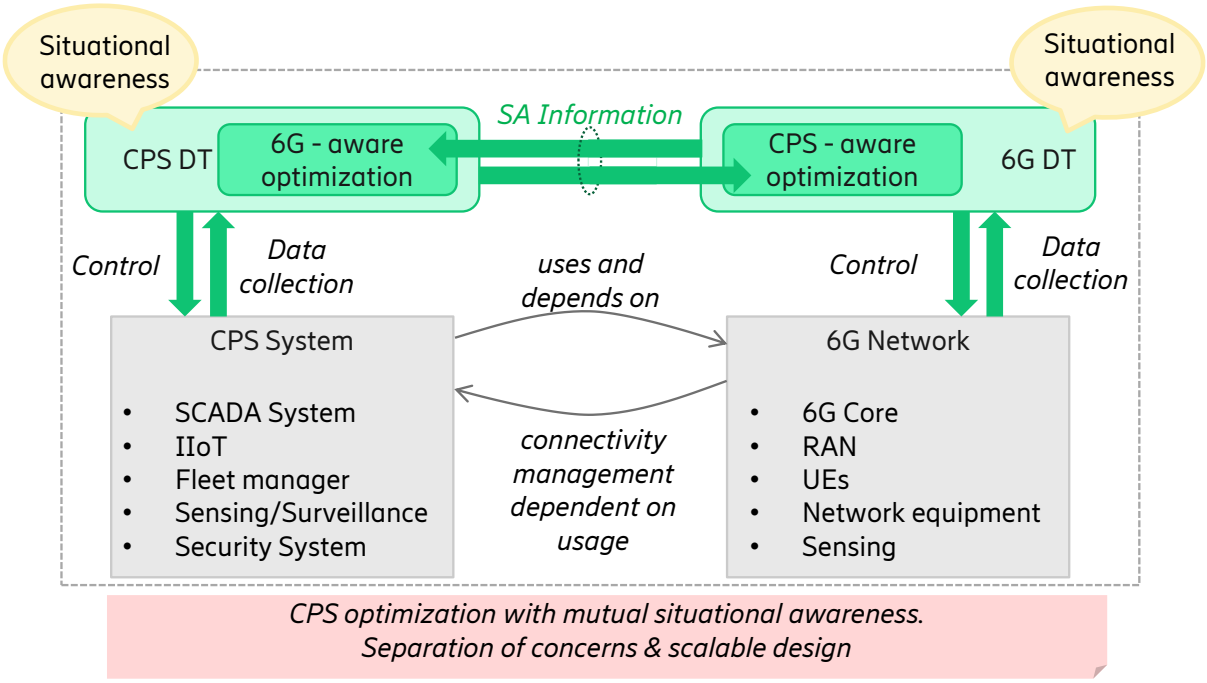


Figure 5-7: Exchange of situational awareness between the digital twin (DT) of a cyber-physical system (CPS) and the 6G DT.

To motivate the benefits of SA and interaction between OT DT and 6G DT we analyze a cooperative AGV use case from [DET23-D11]. This use case implies high mobility of UEs and dynamically changing traffic patterns in the wireless communication network. The 6GS needs to select features and configurations, such as robust transmission modes and enabling fast channel access for time-critical traffic, e.g., via configured grant access, that provide reliable low-latency communication. However, in this use case, the traffic requirements of UEs change depending on their tasks and position on the factory floor. Awareness about current and planned tasks and movements of the UEs provides additional information to the 6GS that can help in planning future resource allocations to fulfill the required QoS for all UEs. For this specific use case we identified three critical operating scenarios that may stress the capabilities of the network. The scenarios are show in Table 5-1.

Scenario	Description
Clustering of UEs	Assuming a large number of UEs on the factory floor, it is possible that they become clustered in a small area, saturating the capacity of the radio cell, especially if this occurs at a location with poor radio link quality.
Poor signal coverage areas	Navigation of UEs through an area with poor coverage. The signal coverage on the factory floor can vary significantly, depending on the radio network deployment and signal blockage due to obstacles. More radio resources are needed to maintain the promised QoS when UEs enter areas with weaker signal coverage.
Dynamic traffic requirements	Change of communication requirements depending on the position of the UEs. A lower latency is required when a UE moves from the safety-relaxed zone to the safety-critical zone or to the processing cell, where required latency reduces and the TP rises. Thus, the 6GS must provision and plan its resources to cope with varying traffic patterns and apply radio resource management methods accordingly.

Table 5-1: Critical operating scenarios

To predict the occurrence of critical scenarios and to mitigate the degradation of QoS, the OT DT and 6G DT have to exchange SA information. We concluded that raw data should not be exchanged between the DTs to keep the separation of concern and privacy and to reduce amount of data to be shared between the two domains. We proposed the sharing of meaningful context-based data, e.g. SA information. Table 5-2 summarizes exchanged data, data direction, actions and data exchange frequency.

	SA direction	SA information	Action	SA frequency
Benefits for OT System	6G DT -> OT DT	Spatial capacity map	OT plans and configures OT processes	SA information is refreshed whenever significant differences occur or it is provided on request, e.g. for a specific path
Benefits for 6G System	OT DT -> 6G DT	Planned OT process requiring communication (time, location/path, traffic profile, QoS requirement). This can include different operation modes to be applied in different spatial zones	6G plans communication needs and may, e.g. reserve radio resources	SA information is refreshed whenever changes in the planned OT process occur

Table 5-2: Summary of SA information exchange

5.6 Key takeaways

- A YANG data model to describe dynamic stochastic port-to-port delay of logical (wireless 5G/6G) TSN bridges. This model provides the essential information about packet delay to the Centralized Network Controller (CNC) executing the algorithms for calculating and adapting end-to-end schedules.
- Different approaches based on the NETCONF protocol and our YANG data model to trigger dynamic adaption of end-to-end schedules. This includes reactive approaches that “only” react to dynamic changes (break-before-make) and proactive approaches that utilize advanced prediction mechanisms for dynamic packet delay to implement a “make-before-break” approach.
- We have proposed wireless-aware end-to-end traffic engineering concepts, which consider the characteristic packet (port-to-port) delay of logical 5G/6G TSN bridges. From our validation of these concepts, we can draw several conclusions. First of all, conventional approaches designed to calculate packet schedules for wireline TSN networks perform poorly with respect to scalability (number of schedulable flows) since they allocate large time slots for packets based on conservative min/max delay bounds. We showed that our wireless-aware scheduling approach based on explicit knowledge of packet delay distributions improves scalability while providing meaningful guarantees on delay.
- Several possible approaches were proposed for the seamless support of 802.1Qbv in a host’s virtualized networking domain. The key finding is that selecting the most appropriate method

requires considering not only the application requirements, but also the capabilities of the compute environment. For proper end-to-end operation, the compute environment's networking capabilities must also be considered when calculating the end-to-end 802.1Qbv schedule, as it might impact the schedule in the communication domain. Through simulations and implementation-based results, we showed that seamless support of 802.1Qbv traffic scheduling for cloudified applications can be achieved efficiently.

- Moreover, we were able to show, by using a Mobile Edge Cloud (MEC) prototype that using MEC reduces delay variation compared to public cloud applications significantly.
- Different options to secure time synchronization were analyzed and In-band Telemetry (INT) was considered as suitable candidate to ensure delivery of time synchronization across the 5G network without adding extra overhead or computing resources.
- The design of a Digital Twin as part of the 5G architecture was defined to collect information about devices and traffic flows, network load, network connectivity characteristics, and other network parameters. The integration of the DT in the 5G system was analyzed to predict the occurrence of critical scenarios and to mitigate the degradation of QoS.

6 DETERMINISTIC6G concept validation framework

To validate the previously described concepts, several validation frameworks have been developed within the DETERMINISTIC6G project, including the 6GDetCom Simulator, a 6GDetCom Delay Emulator, a latency measurement framework and an emulation framework dedicated to security evaluations.

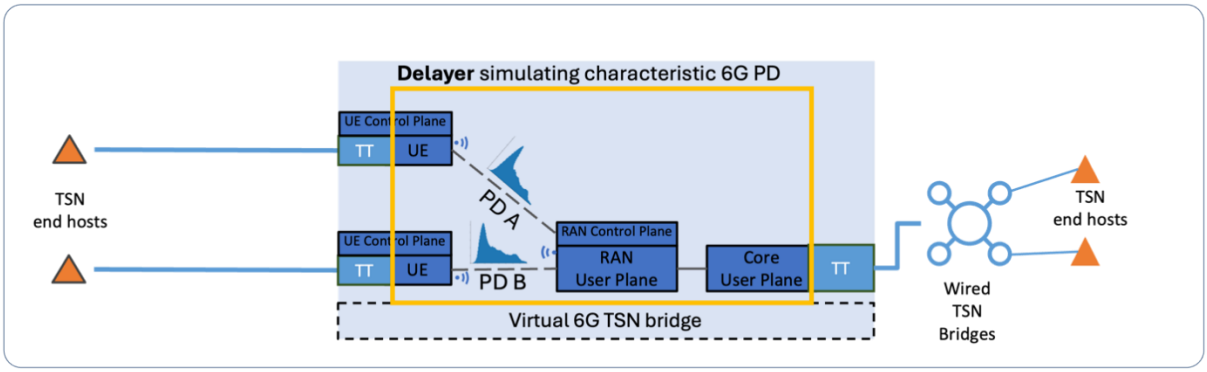


Figure 6-1: 6GDetCom simulator framework architecture

The main enabler of our validation frameworks is the novel data-driven architecture based on latency measurements from a real-world testbed. The general architecture of our approach is depicted in Figure 6-1. In summary, our frameworks utilize a so-called *Delayer* module which replaces the 6G internals by latency distributions based on real-world latency measurements. This approach allows to validate features, concepts and applications at an early stage of development and without requiring access to a real 6G network.

In the following, we explain the key-components of our validation frameworks in detail. First, we describe our latency measurement framework which provides the necessary data for our data-driven architecture. Following that, we describe our two validation frameworks, starting with the 6GDetCom Simulator followed by the 6GDetCom emulator, and we also present some illustrative validation results. Finally, the security validation process on E2E time synchronization is discussed.

6.1 Data-driven latency measurement

The design of End-to-End Delay Analytics Framework (EDAF) is based on the following key principles:

- *Out-of-band Time Synchronization*: To ensure accuracy in one-way delay measurements, the framework employs an out-of-band mechanism for time synchronization. This ensures that all components of the framework use the same time reference when timestamping packets / network conditions.
- *Microservice Architecture*: By adopting a microservice architecture, the framework ensures that different software components and processes are decoupled and can operate independently. This architecture supports scalability, resilience, and ease of deployment, which are crucial for handling the prolonged measurements in 5G networks.
- *Out of Band Data Collection*: Similar to time synchronization, the framework employs an out-of-band approach for data collection. In other words, the measurement data is transported from the measurement points to the data collection and aggregation module via channels distinct from the existing user plane traffic. This method helps in avoiding interference with the measurement process and ensures that the collected data is accurate and not affected by the measurement traffic itself.

The implementation of the latency measurement framework based on the above design involves several components and processes, each aimed at accomplishing a certain design goal:

- *Time Synchronization*: The time synchronization of various components in the framework is accomplished using a Grandmaster Clock (GM) connected to a Global Navigation Satellite System (GNSS) antenna. An out-of-band Ethernet network is used to distribute time synchronization messages of PTP to all hosts involved in the measurement setup. All hosts were equipped with hardware timestamping-capable network interface cards (NICs) to PTP on an out-of-band network.
- *Traffic Generation and Timestamping*: The framework includes a traffic generator that injects network traffic into the 5G system that can mimic real-world application scenarios. The traffic generator is deployed in a client-server model, i.e., a UDP client instance sends traffic with a certain configurable period to the UDP server instance. In addition to traffic generation, the packets are timestamped at the client and the server. This approach helps in measuring the latency experienced by packets as they traverse through the network.
- *COTS 5G Measurement Points*: The Commercial Off-the-Shelf (COTS) 5G system currently does not have capabilities to collect metadata at the COTS base stations. Therefore, a measurement service was developed to be used at COTS UE devices to act as a measurement point. The proposed measurement service is capable of recording a few network conditions (e.g., reference signal receive power (RSRP) and reference signal receive quality (RSRQ) and exposing it on an HTTP server. The collected data provides insights into the latency characteristics of standard network equipment and devices.
- *OAI 5G Measurement Points*: The Open Air Interface (OAI) 5G setup is based on the software 5G implementation of OAI. OAI offers a flexible and open-source platform for experimenting with 5G, allowing for a deeper analysis of packet delay and its variation. OAI 5G provides an opportunity to collect rich amounts of data by inserting measurement points in the different layers of the 5G protocol stack at UE, Radio Access Network (RAN), and/or core. A packet when traversing a layer (e.g., Radio Link Control (RLC)) is timestamped along with the local identifier (e.g., RLC sequence number) as well as network metadata (e.g., number of Protocol Data Units

(PDUs) waiting in the RLC queue). The identifiers are later used to track the end-to-end journey of each packet through the OAI 5G system.

- *Data Collection, Aggregation and Storage*: Collecting data with minimal interference in the user plane traffic is essential, ensuring that the process does not impact the measurement, i.e., packet delay should not be significantly changed due to the introduction of measurement points. Therefore, we selected the LatSeq[5] project as our primary tool for data collection. LatSeq is tailored to extract timestamped information across different layers within OAI.

Real-time aggregation of data from different measurement points in the 5G system and processing the aggregated data is important for the latency measurement framework. To meet this requirement, we follow a microservices architecture (as mentioned in the design) for developing our framework by moving away from the file-based data exchange approach used in LatSeq. The data-aggregator is packaged as a Docker container, which is responsible for gathering data from all measurement points over via socket-based connections.

As probabilistic analysis of packet delay is important for certain applications, it is useful to optimize data storage with respect to that objective. To this end, the latency measurement framework incorporates InfluxDB, a database specialized in time-series data, ensuring the efficient storage of measurements and swift response to queries. The aggregated data can optionally undergo some analytical processing to derive meaningful insights into the network's latency performance. We have implemented simple analytics to demonstrate packet delay decomposition at different delay targets.

It is worth mentioning that implementing and evaluating the latency measurement framework requires a flexible experimentation platform that can facilitate detailed end-to-end experiments. ExPECA [EXPU25] serves as an ideal testbed for wireless communication and edge-computing studies, offering the ability to conduct experiments through the use of COTS 5G as well as Software-defined Radios (SDRs) and OAI 5G for enhanced reproducibility.

Next, we provide a description of how the latency measurement framework can be used to collect measurements on the COTS 5G system.

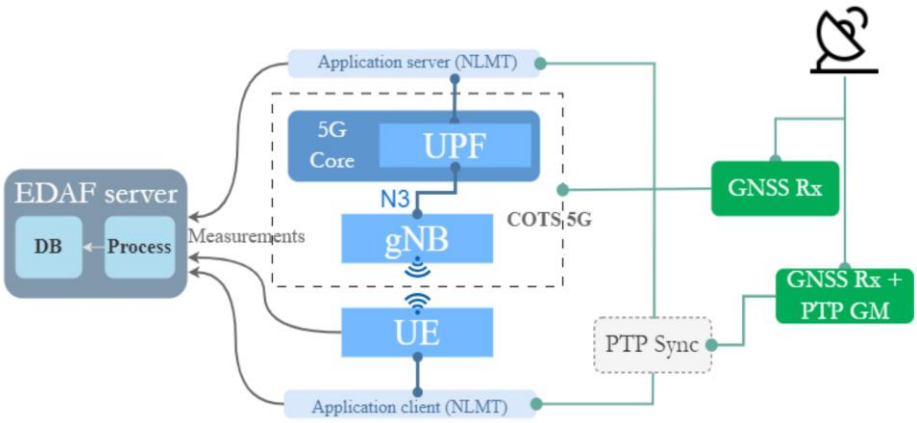


Figure 6-2: Measurement setup for data collection in COTS 5G setup.

[5] https://www.openairinterface.org/docs/workshop/2021-06-SUMMER-VIRTUAL-WORKSHOP/PDF/14_FLAVIEN_RONTEIX_JACQUET_ORANGE_AND_IMT-ATLANTIQUE_LASEQ_LOW_IMPACT_INTERNAL_LATENCY_MEASUREMENT_TOOL_FOR_OAI.pdf

The measurement setup for data collection on COTS 5G setup is shown in Figure 6-2. A key component of the latency measurement framework is the Network Latency Measurement Tool (NLMT). NLMT is based on an existing network measurement tool called IRTT (Isochronous Round-Trip Tester). This tool accomplishes two tasks: (i) traffic generation and (ii) packet timestamping. The UDP packets of a given payload size are generated periodically at a fixed (configurable) interval by the client NLMT instance and are sent towards the server NLMT instance. The packet sequence numbers and timestamps are recorded at both client and server. In addition to this information, network information (RSRP and RSRQ) is sampled at the COTS UE at a fixed interval using a measurement service continuously. This recorded information at client, server and the UE is transported to a remote server for storage and possible analytics.

6.2 DETERMINISTIC6G DetCom simulator framework

The DETERMINISITC6G DetCom simulator framework is our data-driven simulation framework for converged 6G TSN networks and is published open-source on GitHub as the *6GDetCom Simulator*[6]. The architecture as well as the implementation details were presented in the previous deliverables D4.1 [DET23-D41] and D4.4 [DET25-D44]. The goal of the 6GDetCom Simulator is to provide a validation framework for converged 6G/TSN networks to explore the effects novel 6G features and concepts and its effects in TSN networks. In the following we provide a summary of the features of the 6GDetCom Simulator accompanied by a link to the respective showcases on how to use these features in our framework.

As mentioned before, our validation frameworks follow a data-driven approach allowing to embed real-world measurements for an analysis in converged 6G/TSN networks. The 6GDetCom Simulator provides multiple opportunities to embed these:

Packet Delay Histograms: Our simulator allows to draw random delay values from provided histogram files which can be generated from real-world measurements. An example can be found in the "Histogram" section of the *Baseline*[7] showcase.

Closed Form Distributions: Our simulator allows to delay frames on built-in probability distributions, e.g. a normal distribution. This works similar as configuring the packet delay histograms and thus is also part of the *Baseline*[7] showcase.

Random Walk Process: Our simulator allows to produce delay values based on a random walk process. This is presented in the "Random Walk" section of the *Baseline*[8] showcase

Replaying Delay Traces: Our simulator allows to replay delay traces of real-world measurements. These can be either replayed in order or based on the current simulation timestamp. This is presented in the *DelayReplayer*[9] showcase

In the preceding sections, we presented multiple novel 6G concepts developed as part of this project. In the following, we describe which of these features are implemented in the 6GDetCom Simulator and how it allows the validation of these concepts in the context of converged 6G/TSN networks.

[6] https://github.com/DETERMINISTIC6G/6GDetCom_Simulator
[7] https://deterministic6g.github.io/6GDetCom_Simulator/doc/simulations/baseline/doc/index.html
[8] https://deterministic6g.github.io/6GDetCom_Simulator/doc/simulations/baseline/doc/index.html#random-walk
[9] https://deterministic6g.github.io/6GDetCom_Simulator/doc/simulations/delayreplayer/doc/index.html

Above we already explained how we implement latency measurements into our 6GDetCom Simulator. However, mobile networks are typically dynamic leading to changes in the delay distributions or new streams leaving or joining the network and thus requiring an adaption of TSN schedules. To this end, our 6GDetCom Simulator provides functionality to dynamically change streamsets and delay distributions as well as a direct simulation ⇔ scheduler interface to adaptively re-calculate schedules based on these changes. This scheduler interface also provides the scheduler with information about the latency histograms, thus implementing our extension of TSN control plane models as described in Section 5.1. An example using our direct scheduler interface is provided in the *Dynamic Scenario*[10] showcase. In addition to the latency measurements directly embedded in the simulator, RAN latency prediction approaches were developed as part of the DETERMINISITC6G project, as described in Section 4.1. Due to the flexibility of the direct scheduler interface, any scheduler could use these latency predictions to proactively calculate schedules based on these predictions instead of calculating them in a reactive fashion.

Furthermore, Section 4.2 introduced the novel concept of PDC. Our simulation framework directly implements the timestamped PDC approach as well as a simplified version of the virtual timeslot PDC approach. Thus, it allows to evaluate the effects of PDC in converged TSN networks and especially its influence on TSN schedules. An example of PDC in the 6GDetCom Simulator can be found in the *Packet Delay Correction*[11] showcase.

In Section 4.4, the architecture of time synchronization in converged 6G/TSN networks was described. To support this architecture, we first extended the gPTP implementation of INET with support for clock servos (specifically a PI servo-based clock), the BTCA and Hot Standby. Furthermore, we implemented the architecture as described in Section 4.4. This specifically includes the implementation of a 6G clock model as well as a modified implementation of the gPTP module for TSN Translators. An example of the time synchronization implementation can be found in the *Time Synchronization*[12] showcase.

6.3 DETERMINISTIC6G DetCom emulation framework

While our simulator framework described above allows for the simulation and analysis of novel 6G features, it is not straightforward to simulate *real* applications, which would have to be translated to sophisticated simulations models first. To facilitate the testing and evaluation of real applications under 5G/6G networking conditions, we developed the 6GDetCom Emulator, which emulates the characteristic packet delay (PD) of a virtual 6G bridge or the end-to-end delay of an entire TSN network without the need for dedicated 5G/6G hardware. In particular, the 6GDetCom Emulator is used later for the validation of the exoskeleton use case (see Section 6.4.1). In the following, we give a brief overview of the 6GDetCom Emulator. More technical details about the emulator can be found in D4.4 [DET25-D44]. A detailed tutorial on how to use and setup the 6GDetCom Emulator can be found in the GitHub repository[13], as well as in the DETERMINISITC6G blog post[14] describing the network delay emulator.

[10] https://deterministic6g.github.io/6GDetCom_Simulator/doc/simulations/dynamicscenario/doc/index.html
[11] https://deterministic6g.github.io/6GDetCom_Simulator/doc/simulations/packetdelaycorrection/doc/index.html
[12] https://deterministic6g.github.io/6GDetCom_Simulator/doc/simulations/timesync/doc/index.html
[13] https://github.com/DETERMINISTIC6G/6GDetCom_Emulator
[14] https://blog.deterministic6g.eu/posts/2024/10/26/network_delay_emulator.html

The core of the emulator is a Linux Queueing Discipline (QDisc) called sch_delay that can be assigned to network interfaces to add artificial delay to all packets leaving through this network interface. The emulator consists of two major parts: the QDisc running in the kernel space, and a user-space application providing individual delays for each transmitted packet through a character device. The provided delays are buffered in the QDisc, such that delay values are available immediately when new packets arrive. Whenever a packet is to be transmitted through the network interface, the next delay value is dequeued and applied to the packet before passing it on to the network interface (TX queue).

The QDisc can also be applied to network interfaces that are assigned to a virtual bridge on the emulation host to apply individual delay distributions to packets forwarded through different egress interfaces as shown in Figure 6-3, e.g., in uplink and downlink direction of an emulated 5G/6G network. This allows for emulating the end-to-end network delay of a whole emulated network with a single Linux machine within the scalability limits of the emulation host.

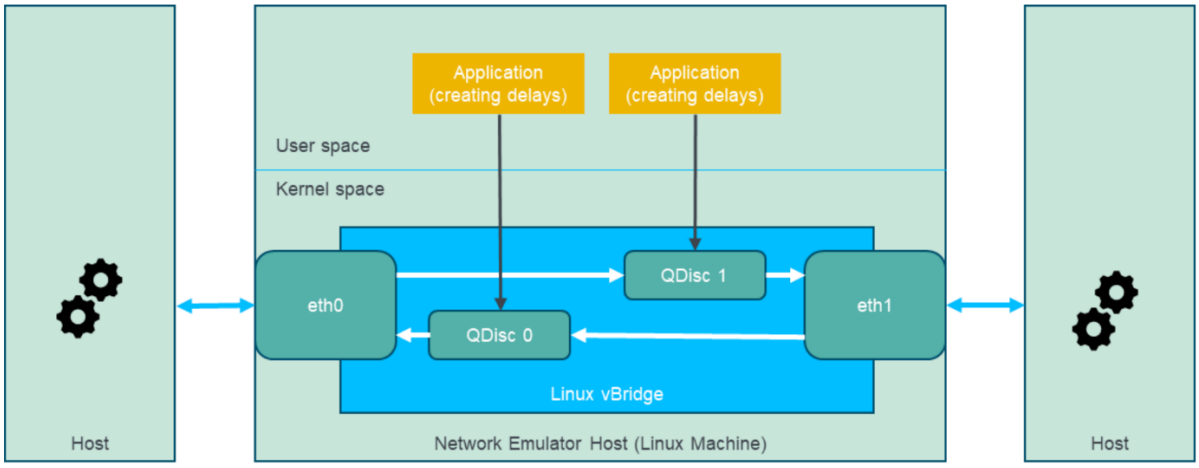


Figure 6-3: Network emulator with individual delay distributions on individual egress interfaces

Figure 6-4 shows the histogram of an emulated wireless delay distribution versus the given reference delay distribution to be emulated. Although we can observe a slight shift of the emulated distribution compared to the reference distribution, our evaluations of the emulation tool show that it can reproduce our target wireless delay distributions with sufficient accuracy. The throughput is limited to about 1 Gbps and the minimum delay that can be emulated accurately is about 100 micro-seconds, whereas our wireless delay distributions are in the range of milli-seconds. Therefore, although this software solution might not be sufficient to emulate wireline delays in the range of micro-seconds, it is sufficient for emulating the PD of wireless 5G/6G networks.

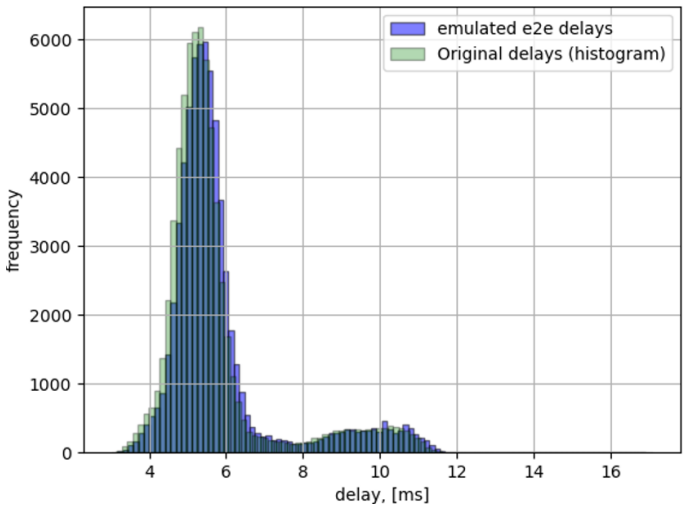


Figure 6-4: Emulated packet delay of wireless network vs. given reference delay

6.4 Concept validation results

Utilizing the validation framework toolset presented before, we next present illustrative validation results. The comprehensive overview of concept validations can be found in [DET25-D45]

6.4.1 Use case validation: exoskeleton

This section describes the work carried out to emulate the effects of a 6G-oriented network in a near-term occupational exoskeleton use case. As outlined in section 4.3 of Deliverable D1.1 [DET23-D11], the near-term scenario involves a wearable occupational exoskeleton to assist worker's movements during repetitive and/or demanding physical tasks.

The active wearable robot described in the scenario includes an embedded processor that runs a low-level controller (LLC), which translates the desired joint assistance torque – computed by higher software layers – into current and voltage setpoints to drive the motors accordingly. The middle-level (MLC) and high-level controllers (HLC) are offloaded to the cloud relying on a 6G-based wireless network.

Offloading the control logic and reducing the onboard hardware components offers several advantages, including reduced cost, size, and power consumption. However, as the device architecture becomes less embedded and based on external computation, it must rely on highly dependable communication to ensure safety and consistency with its use and its risk analysis.

Indeed, emulating this scenario in a well-structured test bench is expected to produce preliminary results that will be extremely useful for effective 6G development.

The overall system architecture is shown in Figure 6-5 and includes:

- IUVO lower limb exoskeleton actuation unit test bench;
- University of Stuttgart 6GDetCom network delay emulator;
- Edge Cloud Server and App emulator.

The test bench (TB), custom-designed by IUVO, is a robotic system capable of applying repetitive and reconfigurable work cycles to the exoskeleton's actuation unit (AU). The AU is defined as the subsystem responsible for converting electrical energy into mechanical power and transmitting it to

assist the user's movements. The test bench is primarily used to perform endurance tests and to evaluate the performance of new exoskeleton designs.

The 6GDetCom network delay emulator is an open-source software developed by University of Stuttgart to assign an artificial delay to a network interface.

The edge cloud server and application emulator is a processing unit capable of executing in real-time (RT) the HLC and MLC off-loaded control layer of the exoskeleton.

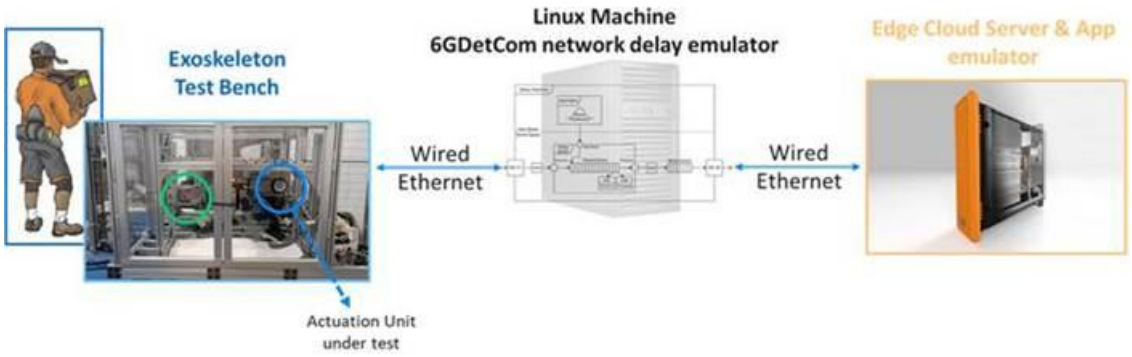


Figure 6-5: Exoskeleton use case validation, overall architecture

Building on the relevant example described in Deliverable D1.3 [DET25-D13] section 2.2, where a worker wears an exoskeleton that supports moving, lifting and handling loads in the warehouse, the assisted walking task is selected for the emulation. Two different walking velocities, 2.5 km/h and 5 km/h, are emulated on the test bench using the same AU assistance profile, which provides ±7 Nm of peak desired torque at the hip joint. The selected assistance profile is representative of a typical worker (body weight: 75 kg, height: 175 cm) walking across the shop floor while carrying a previously lifted small box, with assistance aimed at reducing physical effort and mitigating the risk of injury over repetitive shifts. The parameters selected for the 6GDetCom Network Delay Emulator are the default values (reordering of packets is allowed to closely follow the given delay distribution) and the imported delay distribution is the PD-Wireless-5G-2a which provides packet delay data of a wireless TSN bridge based on measurements from a 5G testbed in an industrial research shopfloor.

To establish reference baselines and evaluate the impact of the 6G network emulation, two different acquisitions are performed for each walking velocity. The first uses the same AU and test bench in a fully embedded architecture. All the control layers LLC, MLC, and HLC are deployed in the AU RT processing unit, relying on AU system on chip deterministic communication protocols. The second uses the architecture previously presented, with the MLC and HLC off-loaded.

An interesting result obtained relates to the time required by the phase detection algorithm of the MLC to properly synchronize with the walking pattern. Table 6-1 shows the measurement results performing multiple consecutive acquisition at a walking speed of 2.5 km/h.

Architecture used for the test:	Phase detection algorithm, synchronization time (seconds):
HLC-MLC-LLC fully embedded	(14±2)s

HLC-MLC Off-loaded with 6GDetCom network emulator enabled	(18±4)s

Table 6-1: Exoskeleton use case validation, test at 2.5km/h and evaluation of the time required to achieve gait phase detection synchronization.

The 14 seconds required by the fully embedded architecture follow the algorithm implemented in the MLC of the test bench. Considering that each step takes approximately 2 seconds at the selected walking speed, the algorithm converges in 7 ± 1 steps. When the HLC and MLC are offloaded and the 6GDetCom network delay emulator is enabled, convergence is on average slower, requiring 9 ± 2 steps. In these final acquisitions, variability also increases in some trials, two extra steps are required to achieve synchronization, while in others this effect is negligible.

Figure 6-6 shows the results of tracking the assistance torque profile. The torque controllers used are the same as those implemented in the final exoskeleton. However, due to the more rigid coupling of the test bench compared to a real human leg, the controller gain was reduced to maintain stability. As a result, the torque profile tracking performance is not optimal when the fully embedded architecture is considered as a baseline. Nevertheless, this architecture demonstrates low variability across consecutive steps, and the error between the desired and actual torque remains stable. On the other hand, the delay introduced by the MLC off-loaded architecture appears to improve the overall average error. However, it also increases variability between steps. Specifically, the variance increases from 1 % at an emulated walking velocity of 2.5 km/h to 25 % and from 2 % to 30 % at 5 km/h.
There are trials where, at a walking velocity of 5 km/h, a large error in the torque loop triggers the safety mechanism, which disables the motor and stops the delivery of the assistance profile.

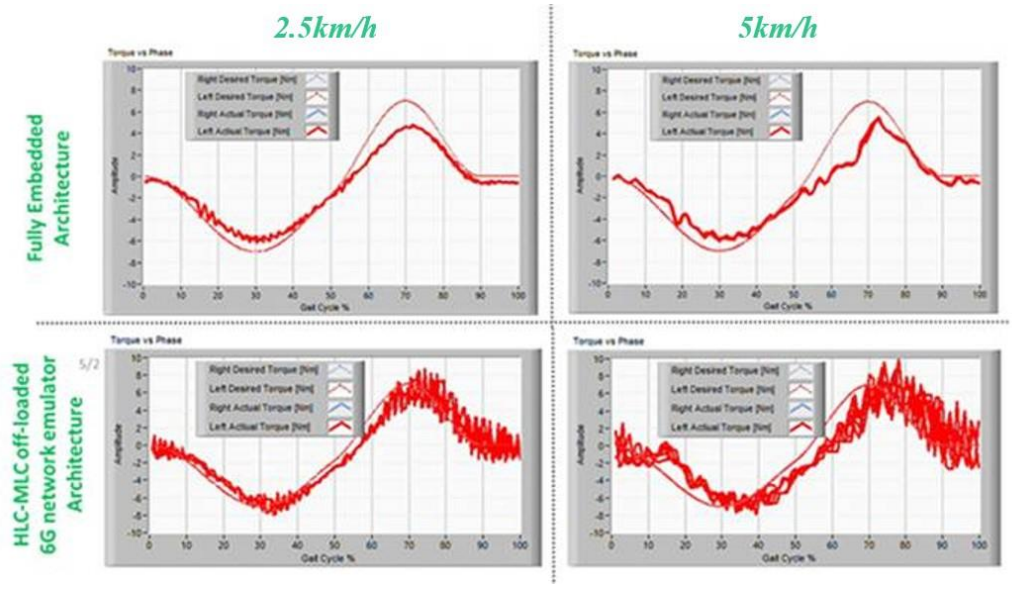


Figure 6-6: Exoskeleton use case validation, torque assistance profile degradation results

The observed degradation in the convergence time of the phase detection algorithms, along with reduced repeatability in tracking the assistance profiles, is particularly critical in real-world use cases involving a human in the loop – especially when the movement is non-periodic or when the high-level controller (HLC) detects a task transition (e.g., from walking to lifting).

The presented emulation system should be used in future studies to further investigate movements performed at different velocities, as well as other types of movements that involve varying assistance profiles. Additional tests using the 6GDetCom Network Delay Emulator – using PD-Wireless-5G-2a and considering Packet Delay Correction or with other distributions such as PD-Wireless-5G-3a, which provides packet delay data for a wireless TSN bridge based on measurements from a 5G testbed implementing standardized ultra-reliable and low-latency communication in an industrial research shopfloor – will be conducted in the future. In general, to achieve the desired assistance specifications and deliver the intended benefits to the user, the described tool can serve as a powerful co-design verification platform for the exoskeleton control layers, algorithms, and communication network.

6.4.2 Use case validation: adaptive manufacturing

In our second use case validation, we considered an adaptive manufacturing use case. The validation scenario consists of Automated Guided Vehicles (AGVs) that are transporting a workpiece on a factory shop floor. The AGVs are controlled from a controller (called Network Control System (NCS) Controller in the following to distinguish it from the TSN network controller (CNC)) running in the edge cloud infrastructure. The AGVs are connected wirelessly via a logical 5G/6G TSN bridge. We use the 6GDetCom simulation framework as validation tool, together with measurements of the characteristic 5G/6G packet delay as captured with the latency measurement framework of our project to define the port-to-port delay of the logical bridge. Figure 6-7 shows the topology of our simulation setup with wireless bridge. As a baseline for comparison, we also replaced the wireless bridge by a wireline bridge (although we are interested to see the difference in performance due to lower packet delay of wireline bridges, a wireline bridge is obviously not a practical alternative in this scenario to connect mobile AGVs).

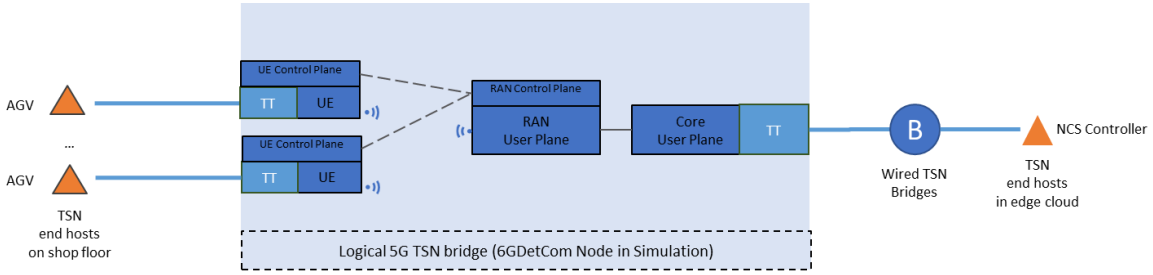


Figure 6-7: Network topology with AGVs, logical 5G/6G TSN bridge, and controller

For a quantitative evaluation of the performance of the system when exposed to characteristic 5G/6G packet delay, we model the AGVs as a textbook example of a networked control system, namely, an inverted pendulum.[15] The inverted pendulum is a pendulum mounted inversely on a cart as shown in Figure 6-8. Obviously, the pendulum is instable and will tip over without control input. In our scenarios, it represents the workpiece that must not tip over while being transported by the AGVs or a liquid transported in an open container that must not spill over – in this respect, the pendulum is even more challenging to control than the real systems mentioned before since the liquid and tall workpiece only become "unstable" when the AGV starts accelerating. The cart can be accelerated by an external force F (control input), and the resulting torque and angular acceleration of the pendulum are used to bring the pendulum into the upright position. The cart represents the AGV, although only moving into one

[15] We also implemented a simulator for the inverted pendulum, whose source code can be found here: https://github.com/DETERMINISTIC6G/InvertedPendulumSimulator

dimension. Besides only controlling the angle of the pendulum, we can also control the position of the cart in addition to simulate the movement of the AGV moving along a given route.

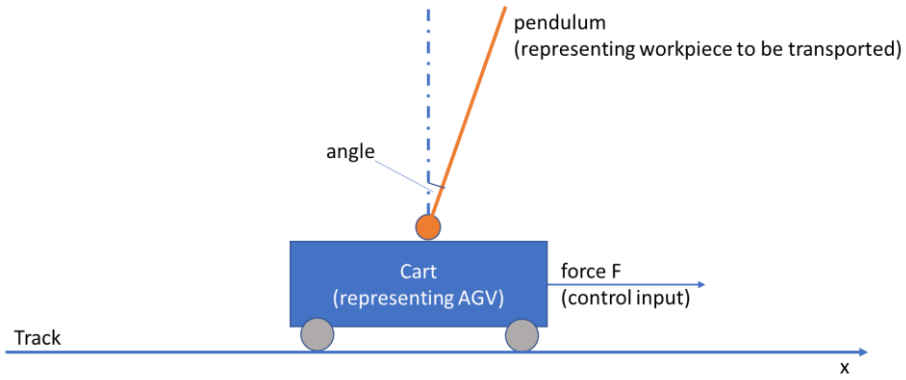


Figure 6-8: Inverted pendulum representing AGV

By considering the position of the cart, we can also model a scenario of two AGVs transporting a workpiece together, while staying within a given reference distance such that the workpiece does not fall off the AGVs, as depicted in Figure 6-9.

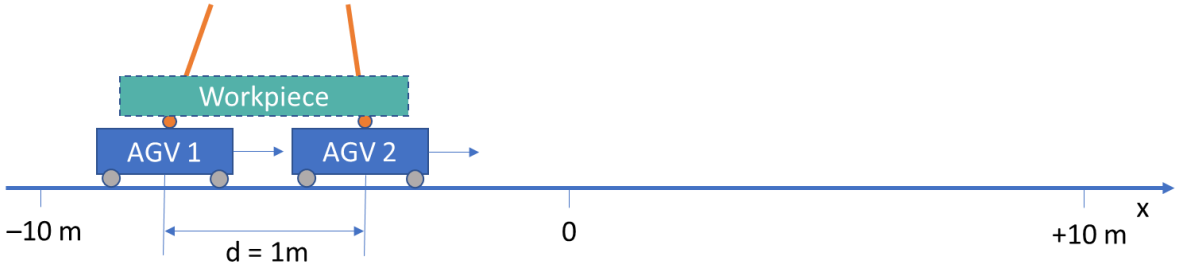


Figure 6-9: Two AGVs (modelled as carts with inverted pendulums) transporting a workpiece together

We also considered different controller types for the control system, namely, Proportional Integral Derivative (PID) controllers and Linear Quadratic Regulators (LQR), so see the influence of the characteristic wireless packet delay onto different controllers.

Figure 6-10 (for wireline system) and Figure 6-11 (for wireless system) show one example of our results: we start the simulation with an angular error of 20 degrees of the pendulum and let the remote NCS Controller, residing in the edge cloud, move the angle to the setpoint zero degrees by accelerating the cart. The numbers show the settling time until the error is within an error band of ± 0.5 degree.

Already with this simple experiment, we can make several interesting observations: first of all, also with characteristic 5G/6G packet delay, the pendulum can be stabilized, although the packet delay of the wireless system is orders of magnitude greater than the delay of the wireline system (milli-seconds vs. micro-seconds). Secondly, the performance (Quality of Control, QoC) of the PID controller degrades with higher delay in the wireless system (longer settling time), whereas the QoC of the LQR stays almost constant. This shows that optimizing the controller on the application layer is an alternative to

optimize the overall system performance, complementary to optimizing the Quality of Service (QoS) of the network.

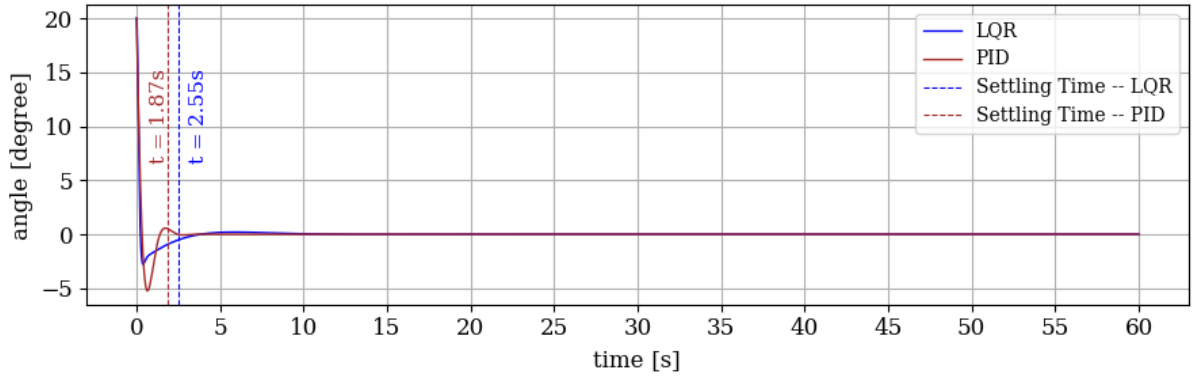


Figure 6-10: Pendulum angle over time – wireline topology

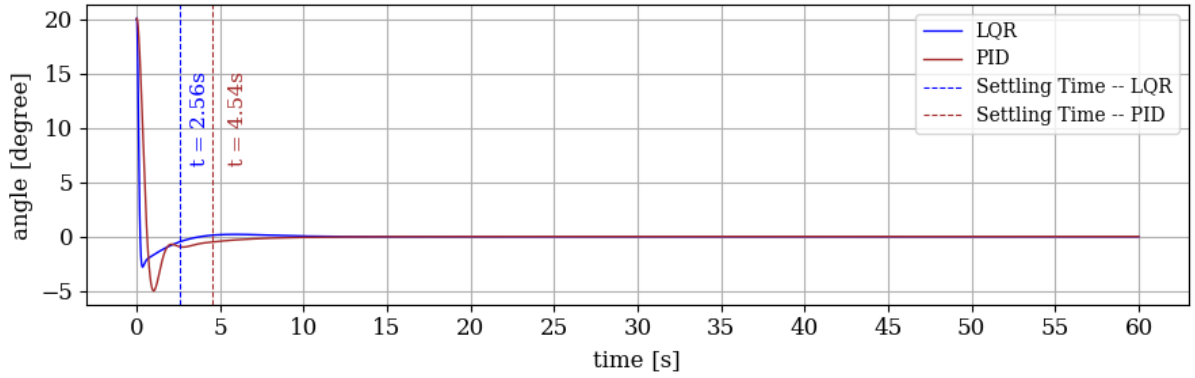


Figure 6-11: Pendulum angle over time – wireless topology

For a detailed description of other results from this use case validation, we refer to Deliverable D4.5 [DET25-D45]. Here, we just briefly summarize our findings:

- The systems under test (pendulum angle control and position control of AGVs), the systems could be stabilized under realistic wireless PD distributions. Therefore, for our exemplary time-sensitive control systems, a wireless 5G/6G network is a viable option, especially attractive for mobile systems.
- The characteristic PD of wireless systems decreases the QoC for some controllers (PID controller in our case) compared to a wireline system with smaller PD. Therefore, further improving the QoS of future 6G networks with respect to latency will have positive impact onto the performance of such time-sensitive systems.
- Selecting an appropriate controller, such as the LQR in our example, for the wireless system – i.e. optimizing on the application layer – is a complementary option to improving the QoS of the network. A cross-layer optimization approach jointly optimizing the control system (application) and network (QoS) would be a valuable extension for future.
- Although our results show that in terms of end-to-end delay the system could be stabilized under realistic PD distributions, we also see that the delay margin until the system becomes unstable is in the range of 10s of milli-seconds only. Therefore, any further delay as added for instance by network congestion must be bounded. To this end, we have proposed wireless-

aware traffic engineering methods that ensure bounded delay also in a network with many streams competing for network resources (see Section 5.2).

- Time-awareness, where components are synchronized to a common time base, has proven to be a useful concept to realize our second exemplary control system with multiple synchronized control systems. This exemplary control system design relies on the availability of a time-synchronization service. To ensure its availability, we have proposed hot-standby mechanisms in our project (see Section 4.4).
- The DETERMINISTIC6G validation framework including the network simulator with 6GDetNet extensions and the latency measurements from the real 5G testbed proved to be a powerful and useful tool to test and evaluate the system under test with realistic wireless networking conditions.

6.4.3 Security validation on E2E time synchronization process

This section presents an implementation of the security-by-design approach proposed earlier, aimed at securing E2E time synchronization using PTP. Further technical details of this technical approach and its implementation are provided in Deliverable D2.4 [DET23-D24] and Deliverable D4.4 [DET25-D44].

Specifically, we emulate a PTP time synchronization network using Mininet, as illustrated in Figure 6-12, where each end-host functions as an Ordinary Clock (OC) and the switch operates as a Transparent Clock (TC). The OC is implemented using LinuxPTP, while the TC is developed with the P4 language (Programming Protocol-Independent Packet Processors), enabling custom data-plane logic tailored to timing security. By leveraging programmable data planes, the framework utilizes In-band Network Telemetry (INT) to embed monitoring data directly within PTP extension fields. This approach eliminates the need for additional probe packets and significantly reduces network traffic overhead. An INT collector module is responsible for capturing PTP packets, extracting embedded telemetry data, and enabling real-time detection and localization of TDAs.

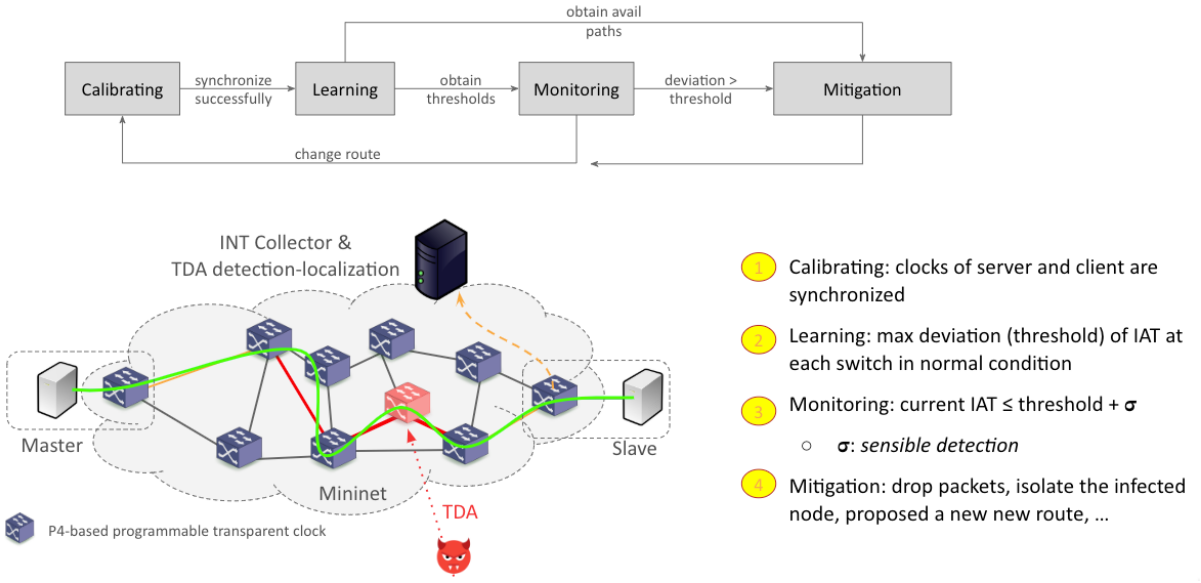


Figure 6-12: Mininet-based emulator of TDA & detection in E2E time synchronization

It is worth noting that when PTP messages traverse a 5G/6G system, the system effectively functions as logical TC. As can be seen in Figure 6-13, the 5G system consists of a core network with a user plane function (UPF), and a radio access network including base stations (gNBs) and user equipments (UEs). The device-side TSN translator (DS-TT), appended to the UE, and the network-side TSN translator (NW-TT), appended to the UPF, are the entities in charge of handling the PTP messages in the 5G data plane. Calculating the 5G residence time and inserting it in a PTP message is part of the DS-TT's and NW-TT's responsibilities.

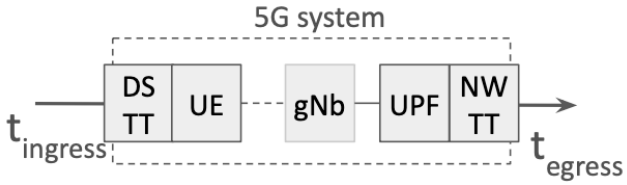


Figure 6-13: Time synchronization over a 5G system acting as a logical PTP transparent clock

TDA can unintentionally occur in a TC when the correctionField does not reflect correctly the residence time of its message. For example, in the time synchronization over a 5G system, a vital prerequisite for correctly calculating the residence time in this logical TC is that the $t_{ingress}$ and t_{egress} are timestamped by a single reference clock. In other words, it requires that the clocks of the DS-TT and the NW-TT are perfectly synchronized. Otherwise, a TDA can occur in such a logical TC.

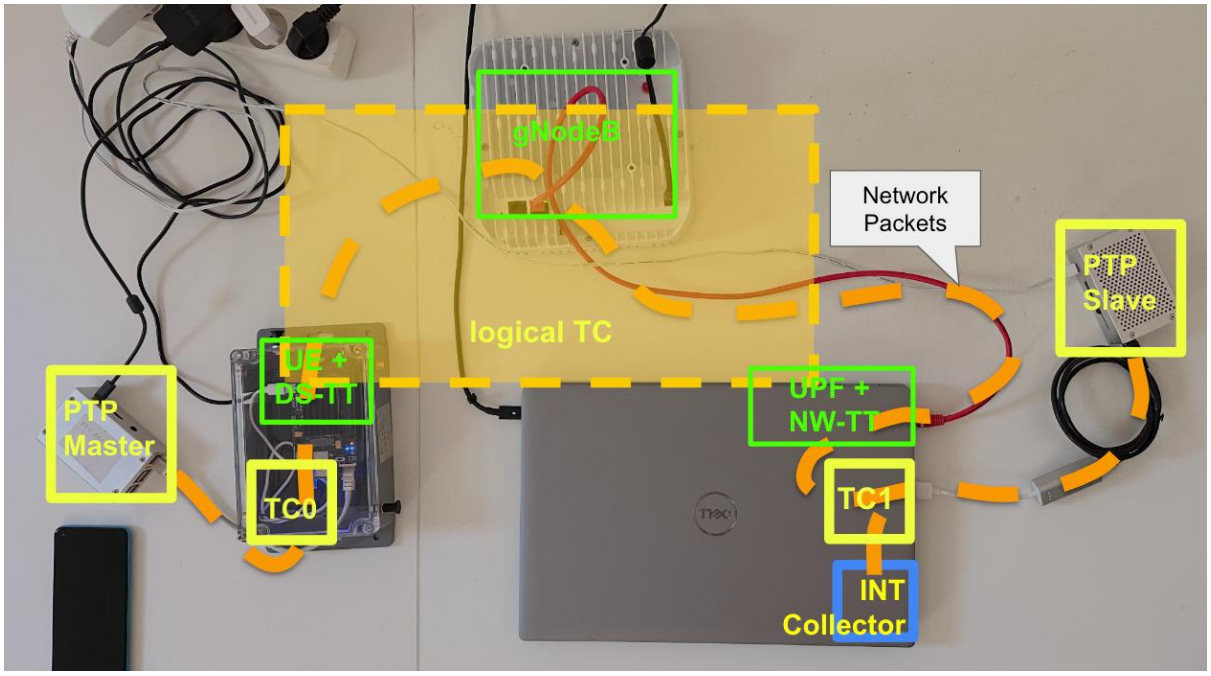


Figure 6-14: Secure PTP time synchronization over a 5G network

Figure 6-14 illustrates the physical testbed used to simulate TDAs and evaluate detection mechanisms targeting PTP synchronization over a 5G network. The setup consists of three TCs, one of which is a logical TC emulating the 5G system. A TDA scenario is triggered when there is a time misalignment between the User Equipment (UE) and the User Plane Function (UPF), disrupting accurate timestamp synchronization.

It should be highlighted that the Mininet-based emulation approach, which utilizes software timestamping, eliminates the need for specialized hardware and allows for the flexible emulation of multiple clocks with ease. Figure 6-15 demonstrates a scenario in which the emulation network combines with real PTP client/server. The scenario can be to emulate TDAs which can occur between them to evaluate the TDA tolerance of these PTP devices.

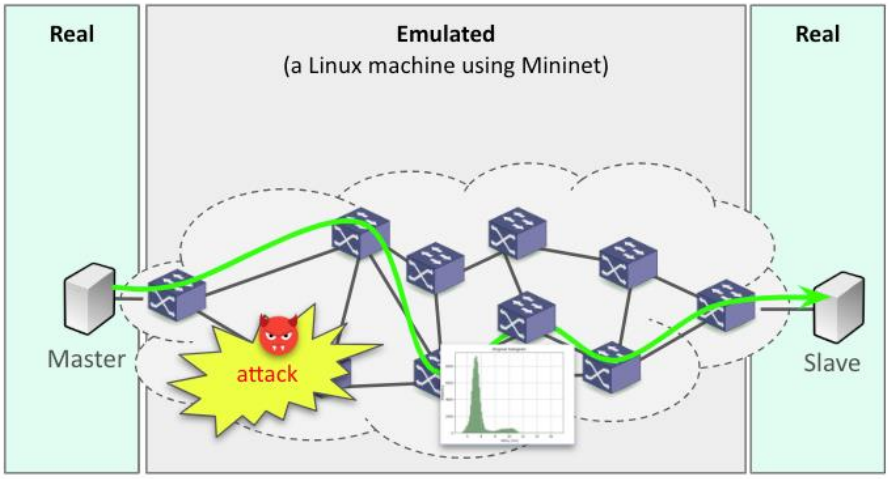


Figure 6-15: Secure PTP time synchronization over a 5G network

The TDA detection in our framework is carried out in four key phases: calibration, learning, monitoring, and mitigation, as described below:

- Calibration Phase: This phase occurs when the PTP slave initially begins synchronizing with the PTP grandmaster. During this period, the clock offset values are relatively large and exhibit significant variation. Over time, these offsets gradually decrease and stabilize. The calibration phase ends once the client achieves synchronization with the server.
- Learning Phase: Executed after successful synchronization, this phase assumes that the time synchronization network is operating under normal conditions, free of TDA interference. Its goal is to determine the maximum clock offset tolerated by the system, i.e., the accuracy the network can maintain. This accuracy must meet the predefined requirements. Additionally, the learning phase establishes a threshold representing the maximum acceptable variation in inter-arrival times (IAT).
- Monitoring Phase: In this phase, the framework continuously monitors the time synchronization network to detect and localized TDAs. It calculates updated values of IAT variation. An alert is triggered if (i) it is greater than the threshold determined in the learning phase above and (ii) it can cause a clock offset bigger than the given requirement.
- Mitigation Phase: This phase is planned as future work, as it may require interaction with a Centralized Network Controller (CNC). Potential mitigation strategies include isolating the malicious segment of the network and proposing an alternate path that maintains equivalent end-to-end delay while reusing as much of the original path as possible.

The experimental results demonstrate that the proposed solution effectively maintains synchronization accuracy. The P4-based TCs exhibited performance on par with conventional LinuxPTP-based TCs. During the initial synchronization phase, clock offset values were elevated, as expected, but they stabilized rapidly. Once calibration was complete, the offsets consistently

remained below 150 microseconds, aligning with the accuracy typically achieved using Linux software timestamping. These results confirm that the use of programmable TCs does not compromise synchronization quality and that they are fully suitable for deployment in time-sensitive networking environments.

The integration of INT into PTP messages proved highly effective for monitoring synchronization behavior across the network. By embedding telemetry data directly within existing PTP extension fields, the solution enables real-time visibility into packet timing characteristics without generating additional overhead. The collected telemetry allows for tracking of propagation delays across multiple hops, offering valuable insights into network behavior and highlighting irregularities that may impact synchronization performance.

Most importantly, the validation confirmed the system's ability to detect and localize TDAs. By monitoring variations in timing between messages, it was possible to pinpoint the presence and location of delay anomalies. These insights were derived without requiring perfect clock synchronization between devices, demonstrating the robustness and practicality of the approach.

This evaluation validates the feasibility and effectiveness of a security-by-design framework for protecting PTP-based time synchronization in dependable deterministic networks. Through the integration of INT telemetry, P4-based programmable TCs, and continuous monitoring, the system provides a reliable means of detecting subtle delay-based attacks that are often undetectable by conventional mechanisms. The approach supports real-time, packet-level analysis and lays a strong foundation for future extensions involving automated response and mitigation, offering a promising path forward for resilient, software-defined, time-sensitive network infrastructures.

As future work we also need to consider the case where an INT data collector could be compromised. To be able to detect this and prevent it from affecting the correct detection of delay-based attacks, several observation points need to be enabled so that any misbehaving one can be detected and ignored.

6.5 Key takeaways

As a first takeaway, we can state that DETERMINISTIC6G validation framework consisting of the 6GDetCom Network Simulator, the 6GDetCom Network Delay Emulator, a latency measurement framework to gather characteristic 5G/6G packet delay data, and an emulation framework dedicated to security evaluations has proven to be very effective in validating our concepts for dependable 6G communication. The 6GDetCom Simulator together with realistic latency measurement data from the measurement framework offers a unique tool that, for the first time, enables the systematic evaluation of the impact of characteristic 5G/6G packet delay in TSN networks with wireless and wireline TSN bridges and end systems. Using realistic network delay and processing delay data, gathered in an edge cloud environment, we are also able to evaluate the end-to-end performance “over-the-loop” from sensor, to controller, to actuator in time-sensitive networked control systems. The 6GDetCom Network Delay Emulator enabled the performance evaluation of real applications – in our case an exoskeleton – with realistic 5G/6G packet delay. The security emulation framework enabled the validation of our security-by-design approach targeting attacks on the Precision Time Protocol. Using this comprehensive validation framework, we have produced a number of interesting validation results, from which we can draw the following conclusions.

With respect to measurements and characterization of RAN latencies, the EDAF tool allowed for delay decomposition in a running mobile network. We could show through a staged experimentation how different delay elements vary and contribute to the overall end-to-end delay, providing a novel level of explainability.

The validation of security mechanisms was focused on time delay attacks. Our validation shows that our proposed monitoring framework, based on P4 and in-band network telemetry (INT), enables the accurate detection and localization of time-delay attacks even in challenging situations where the attacker introduces only subtle, asymmetric delays without modifying the content of packets. Therefore, we conclude that our software-defined security-by-design approach based on INT and real-time packet-level monitoring is effective to enhance the resilience of deterministic networking systems, without relying on specialized hardware.

In our first use case validation, we studied the effects of offloading the control of an occupational exoskeleton to a remote server via a wireless network using our exoskeleton prototype and 6GDetCom Network Delay Emulator. In this system, we observed an impact of the characteristic packet delay onto the phase detection algorithm together with a reduced repeatability in tracking the assistance profile. In particular, this is critical in real-world use cases with humans in the loop, non-periodic movement, or task transitions (e.g., from walking to lifting). The results encourage further studies as part of future work like movements performed at different velocities, as well as other types of movements that involve varying assistance profiles.

Our second use case validation of an adaptive manufacturing scenario showed the impact of the characteristic packet delay (as measured with our latency measurement framework) of wireless 5G/6G networks onto different networked control systems (simulated with the 6GDetCom Simulator). This validation showed that it is possible to implement a control loop over a wireless network with realistic packet delay to stabilize the open-loop-unstable system. An increase in characteristic packet delay decreased the quality of control for some controllers, while others showed to be more robust to packet delay. Therefore, we conclude that, on the one hand, it is beneficial to further decrease the latency of wireless networks. On the other hand, optimizing the controller on the application-layer is a complementary approach to optimizing the end-to-end performance of the networked control system. Moreover, isolating streams in the network and avoiding congestion through wireless-aware traffic engineering techniques as discussed above are required since the investigated control systems showed a small delay margin before becoming unstable. We also showed in this use case how time-awareness facilitates the implementation of control systems relying on synchronized components. Such systems directly benefit from techniques ensuring high-availability of a time synchronization service, building, for instance, on our hot-standby techniques already mentioned above.

7 Dissemination, communication and exploitation

Communication, dissemination, and exploitation have been crucial tasks during the entire lifetime of DETERMINISTIC6G project, as it is recognized that they are significant elements to increase visibility and the impact of the project. As the DETERMINISTIC6G aims to define and develop new fundamental concepts for 6G dependable, time-critical communication technology for innovative applications, it is essential to ensure the successful adoption of its technology across the eco-system and to define a comprehensive dissemination, exploitation, and communications strategy to provide relevant information to all stakeholders and facilitate market adoption of the project results. In this regard,

Table 7-1 presents the strategy, along with a summary of proposed impact, dissemination targets and achieved results.

Category	KPI	Targets	Achieved
Standard contributions	Standards and impact to standards groups	3GPP (SA1, SA2, RAN1, RAN2) Future revision of IEC/IEEE 60802 Intended new amendment to IEEE 802.1Q OPC UA FX framework	17 (3GPP) 9 (IEEE) 5 (IETF)
	Number of contributions	30	31
Industry and scientific community	Keynotes and panels in major conferences	at least 6 keynotes and at least 2 panels	29 keynotes and talks 6 panel discussion (EuCNC, O-RAN, 6G summit Dresden, Berlin 6G Conference, MeditCom)
	Number of publications (journals, conferences)	30	24 (published) 5 (under review)
	Workshops in major conferences	at least 2	7 (organized)
	5GPPP/6GIA activities	Contribution to steering board, technology board, pre-standardization, architecture, vision, and societal challenges	6GIA webinar, SNS journals, SNS video, Contribution to SNS 6GIA workshop at EuCNC, involvement in the 6GIA WGs and white papers
	Tutorials		Half-day tutorial at European Wireless'23 IEEE 802 Plenary, Berlin, Germany
	Special session		Special session at EuCNC 2023
	Webinar series		3 (conducted) Joint webinar with sister SNS projects
Influence towards academia	Training activities (summer schools)	2	2 conducted
	Graduate, PhD courses	3	7 Master courses

Communication towards the general public	Website visits outside consortium	1000+	3275 (unique hits)
	Press release, research blog	10+	11
	Social media channel used	X, LinkedIn, YouTube	Active

Table 7-1: Summary of proposed dissemination targets and status

7.1 Scientific dissemination and public communication

DETERMINISTIC6G prepared and attended a significant number of workshops, conferences and events, covering the main technical objective of the project: 6G architecture and conceptual solutions for dependable, time-critical communication. The project members have delivered keynote speeches at various forums and have participated in several panel sessions organized both by DETERMINISTIC6G as well as by other projects.

The project actively participated in 6G-IA collaboration activities (e.g., contributing to white papers, participating in 6G-IA organized workshops and events), primarily through the 6G Architecture WG and the Pre-standardization WG. In addition, DETERMINISTIC6G organized various events (e.g., webinars and workshops) together with its sister projects. Furthermore, DETERMINISTIC6G contributed to the preparation of a '6G book' – led by Hexa-X-II project - focusing on the architectural and functional aspect of 6G dependable communication and compute.

The project also placed strong emphasis on disseminating the results within the academia, to strengthen the understanding of 6G-enabled dependable, time-critical communication by organizing summer schools and supporting graduate and PhD courses.

In terms of number of publications, the currently accepted papers are below the target, but the publications needed to meet the target have already been prepared and submitted, and – as shown in Table 7-1 – are currently under review.

The final project results and deeper insights into the various technical areas have been presented at the end of the project in a joint Summer school and Project summit event in Stockholm.

7.2 Standardization and regulation activities

A key communication and dissemination objective of the DETERMINISTIC6G project is to contribute to standardization and pre-standardization activities to exploit project innovation in European and worldwide market.

While in the first period of the project the focus of the standardization was on 3GPP, in the second phase the focus shifted towards IEEE and IETF. In total, DETERMINISTIC6G prepared 31 standardization contributions, exceeding the original target. A major achievement in the standardization was – based on the results of the project – the initiation of a new standardization activity in IEEE, as an extension of IEEE802.1Q. The goal of this amendment (P802.1Qee) is to specify procedures and YANG data models for traffic engineering in bridged networks that incorporate wireless technologies with stochastic delay characteristics.

8 Conclusions

The objective of DETERMINISTIC6G was to establish the foundations for dependable, time-critical communication and compute for 6G visionary use cases, addressing both architectural and conceptual aspects. The methodology of the project followed a combined approach comprising 1) the development of features capable of characterizing and mitigating the stochastic characteristics of the 6G wireless communication and compute system components and 2) the extension of legacy traffic engineering solutions with wireless-friendly capabilities that embrace the inherent uncertainties of the wireless and compute systems.

In line with the objectives, the key takeaways of the project:

- Leveraging detailed use case analysis and the identification of use case KPIs and KVIs, a comprehensive dependable service design framework has been developed. This framework comprises a complex service specification toolset for the applications, as well as provides an operation model and methodology for dynamic adaptability of dependable services, enabling the reaction to the changing performance of stochastic system components.
- Development of a data-driven latency characterization and prediction framework capable of predicting the full probability distribution of end-to-end delays, instead of only point estimates, providing a crucial input for wireless-aware scheduling mechanisms. In addition, a delay-aware RAN design is proposed, where the observability of latency performance can be integrated into the 6G radio protocols, providing input for the data-driven prediction.
- As 6G features for dependable, time-critical communication, various 6G packet delay correction methods and RAN resource allocation mechanisms have been developed to mitigate the stochastic behavior of the wireless systems and enable seamless integration with legacy TSN solutions.
- Extensive architectural and functional analysis of how reliable time-synchronization can be provided by 6G systems.
- Development of various wireless-aware traffic engineering concepts, taking into account the latency characteristics of a virtual 5G/6G TSN bridge in an end-to-end, integrated 5G/6G-TSN deployment. In conjunction, a novel concept for modeling the dynamic characteristics of a wireless system has been introduced. This enables the provision of sufficiently detailed information on the stochastic latency characteristics of a virtual 5G/6G-TSN TSN bridge to the TSN control plane (CNC). Combined with the wireless-aware scheduling concepts, a comprehensive end-to-end 802.1Qbv schedule can be designed by the CNC.
- User plane methods have been devised to ensure the seamless support of 802.1Qbv traffic handling in the virtualized networking of a compute (cloud/edge) host. In addition, a control-plane model has been proposed to describe the cloud hosts' capabilities to the TSN control plane, enabling to plan the proper traffic handling for cloudified application instances.
- Detailed description of the interaction between the OT and 6G Digital Twins.
- Design of a comprehensive end-to-end security framework for dependable networking, with a special focus on how threats affect time-synchronization protocols, and on applicable threat detection and mitigation strategies.
- Development the 6GDetCom open-source simulation framework, which is the first framework to enable the realistic simulation of a converged 6G – TSN deployment, by considering the stochastic latency characteristics of 5G/6G logical TSN bridges, as well as processing delay for applications and services in the compute domain.

- Development of a 6GDetCom Emulator, which emulates the characteristic packet delay of a virtual 5G/6G bridge or the end-to-end delay of an entire TSN network.
- Establishment of a latency measurement framework, capable of capturing detailed 5G/6G latency data, including the description of various latency components and associated network conditions to develop realistic latency models for 6G-DetCom bridges.
- Comprehensive description of the 6G system architecture tailored to dependable communication, outlining the functions developed in the project and their interworking.

In summary, DETERMINISTIC6G successfully showcases an essential feature set for realizing 6G-enabled dependable, time-critical communication and compute services. Moreover, the project has laid down the foundation for further exploitation, future research and development, and closer collaboration among ecosystem partners. Overall, the project has contributed significantly to the ecosystem for a converged cyber-physical continuum.

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List of abbreviations

AI	Artificial Intelligence
AQM	Active Queue Management
BTCA	Best timeTransmitter Clock Algorithm
CDE	Conditional Density Estimation
CNC	Centralized network controller
CNI	Container Network Interface plugin
COTS	Commercial off-the-shelf
CPS	Cyber Physical System
CQF	Cyclic Queuing and Forwarding
DT	Digital Twin
DS-TT	Device-Side TSN Translator
DetNet	Deterministic Networking
DVP	Delay Violation Probability
E2E	End-to-end
EDAF	End-to-End Delay Analytics Framework
FIPS	Full Interleaving Packet Scheduler
GM	Grandmaster
GMM	Gaussian Mixture Model
GMEVM	Gaussian Mixture Extreme Value Model
GPD	Generalized Pareto Distribution

HARQ	Hybrid Automatic Repeat Request
ICT	Information and Communication Technology
IDS	Intrusion Detection System
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
INT	In-band Network Telemetry
KVI	Key Societal Value Indicator
KPI	Key Performance Indicator
LSTM	Long Short-Term Memory networks
MCS	Modulation and Coding Scheme
MDN	Mixture Density Network
MEC	Multi-Access Edge computing
ML	Machine Learning
MLP	Multi-Layer Perceptron
NEF	Network Exposure Function
NIC	Network Interface Card
NWDAF	Network data analytics function
NW-TT	Network-Side TSN Translator
OAI	Open Air Interface
OE	Occupational Exoskeleton
O-RAN	Open Radio Access Network
PDC	Packet Delay Correction
PDF	Probability Density Function
PDV	Packet Delay Variation
PLC	Programmable Logic Controller
PTP	Precision Time Protocol
RAN	Radio Access Network
RAP	Resource Allocation Protocol
RLC	Radio Link Control
RSRP	Reference Signal Receive Power
RSRQ	Reference Signal Received Quality
SA	Situational Awareness
SDR	Software-defined Radio
SMD	Security Management Domain
STI	Strict Transmission Isolation
TAPRIO	Time-Aware Priority Shaper
TBS	Transport Block Size
TDA	Time-Delay Attack
TLV	Type-Length-Value
TSCAI	Time Sensitive Communication Assistance Information
TSCTSF	Time Sensitive Communication and Time Synchronization Function

TSN	Time Sensitive Networking
UE	User Equipment
XR	Extended Reality
ZSM	Zero-touch Service Management