DETERMINISTIC6G

First Intermediate Project Report

D6.3

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First Intermediate Project Report

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V0.2	Draft for internal review
V1.0	Final version

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Executive summary

This first intermediate project report contains an overview of the results attained in DETERMINISTIC6G up until the writing of this report (i.e., project first year end). The main achievements are highlighted, and references are provided to the relevant deliverables and other documents. All work packages have been progressing substantially and reached their corresponding milestones, while some of the work packages have even been overachieving their planned tasks. This is reflected in the deliverables produced by DETERMINISTIC6G, which towards the end of the first year stands at 6 deliverables, coming from all work packages. Specifically, the main outcomes are: (1) for WP1 the definition of four broad and novel use cases with detailed definitions in terms of KPIs, footprints and KVIs; (2) for WP2 the validation of the prediction framework as well as the specification of packet delay correction concepts, that can be operated in accordance to deterministic end-to-end protocols like TSN and DetNet; (3) for WP3 the definition of several options to incorporate stochastic elements into deterministic end-to-end protocols, enabling a better integration of wireless 6G systems in the future, as well as the first definition of an end-to-end relevant security framework; (4) for WP4 the first implementation of a simulation framework for layer 2 TSN-compatible evaluation of end-to-end performance taking also wireless 6G systems into account. In addition, WP5 has already achieved first outcomes regarding impact creation. Based on the outcome of the first year, we expect a steady continuation of the research and impact creation during the following year.

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 in particular important for mobile components, like vehicles, mobile robots, or wearable devices. This approach leads to an increasing need for communication between physical and digital objects, and this communication can span over multiple communication and computational domains. Communication in this cyber-physical world often includes closed-loop control interactions which can have stringent 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 will last for 30 months. The total project budget is roughly 5.5 million Euros and there are around 21 full time person equivalent working during the project duration from 12 partners and 2 linked partners.

The main goal 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.

Figure 1 shows the structure of the project, illustrating the different focus areas of the targeted work and the work packages addressing them.

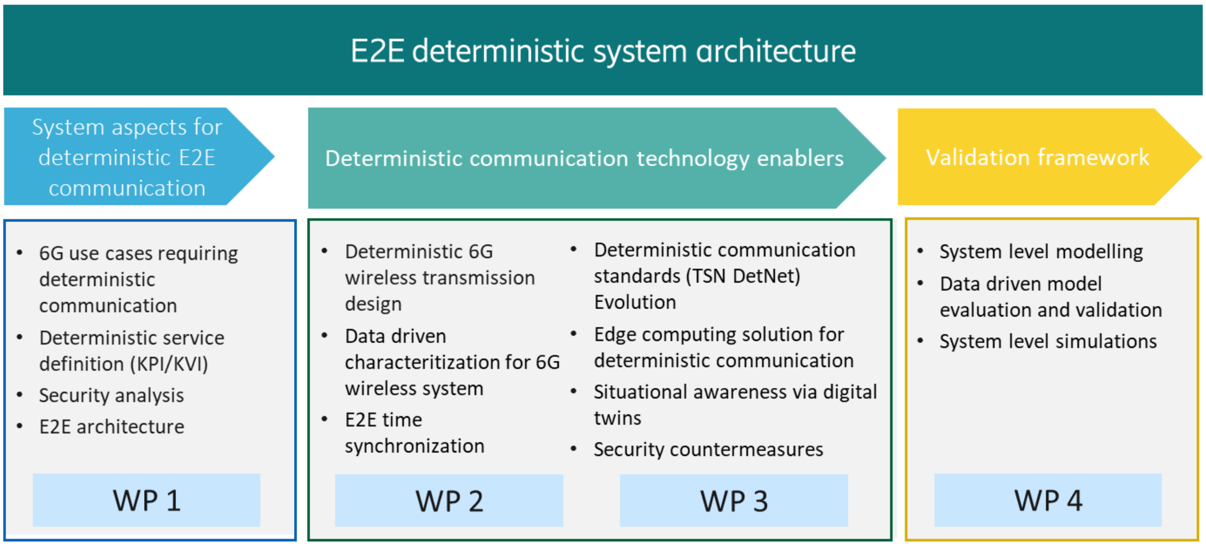


Figure 1 – DETERMINISTIC6G project structure

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. Furthermore, this work package is responsible for the definition and the elaboration of the DETERMINISTIC6G architecture in end-to-end scope (WP1).
- Development of 6G centric enablers for ensuring deterministic communication services, by considering the use case requirements. Among other things, this work deals with packet delay correction (PDC) solutions, data-driven methods for latency prediction in 6G systems, as well as resource allocation strategies in RAN (WP2).
- Further developing the existing deterministic communication systems (e.g., IEEE 802.1 Time Sensitive Networking, IETF Deterministic Networking) to enable them to consider the capabilities/limitations of the 6G wireless networks in the most efficient way (WP3).
- Edge computing modeling to ensure deterministic operation, development of a security framework and digital twinning of the 6G system (WP3).
- One major goal of the project is to validate the concepts that are carried out in WP2 and WP3, therefore a simulation and concept validation framework is developed (WP4).

1.1 Objective of the document

The purpose of this document is to summarize the progress made in DETERMINISTIC6G during the first year of the project. The main conclusions and takeaways from the deliverables already produced within DETERMINISTIC6G are collected, moreover, a brief overview of all ongoing activities, as well as an outlook on the next steps are provided.

Since this document is an intermediate project report, its scope and objectives are very much aligned with the objectives of the project, which are the following:

1. Definition of deterministic services including KPIs and KVIs for upcoming 6G visionary use cases.
2. Design and develop 6G features for deterministic wireless transmission and wireless-friendly enhancements for TSN and DetNet.

3. Develop AI/ML based techniques for data-driven latency characterization of 6G wireless systems.
4. Develop 6G time synchronization solution to ensure E2E time awareness and new concepts for deterministic edge cloud solution for compute/communication integration in the 6G system.
5. Conceive a security architecture and framework for 6G deterministic communications.
6. Develop a validation framework for new 6G concepts.

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 to the achievements of DETERMINISTIC6G made in the area of use cases, which require dependable time-critical communication. This section also overviews the work towards the DETERMINISTIC6G E2E architecture. Section 4 focuses on the results achieved regarding 6G centric enablers for dependable, time-critical communication. Section 5 gives an overview about the wireless friendly system design, time-aware edge computing deployment, security design, as well as the framework and usage of digital twins for situational awareness in 6G systems. In Section 6 the first release of the simulation and validation framework is discussed. Section 7 provides an overview of the dissemination and communication efforts in the project. Section 8 presents the conclusions of the document and gives an outlook on the expected continuation of the work in the rest of the project.

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

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 for compute and communication elements, and also applications, that any stochastic behavior can be minimized such that the time characteristics of the element can be clearly associated with tight minimum/maximum bounds. Cloud computing provides efficient scalable compute, but introduces uncertainty in execution times; wireless communications provides flexibility and simplicity, but with inherently stochastic components that lead to packet delay variations 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 compute 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 allowing for adaptation between applications running on top such converged and managed network infrastructures. The idea is to introduce flexibility in the application operation such that its requirements can be adjusted at runtime based on prevailing system conditions. This encompasses a larger set of application requirements that (a) can also accept stochastic end-to-end KPIs, and (b) that 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, we extend a notion of deterministic communication (where all behavior of network and compute nodes and applications is pre-determined) towards dependable time-critical communication, where the focus is on ensuring that the communication (and compute) characteristics are managed in order to provide the KPIs and reliability levels that are required by the application. DETERMINISTIC6G facilitates architectures and algorithms for scalable and converged future network infrastructures that enable dependable time-critical communication end-to-end, across domains and including 6G.

3 Use cases, architecture and system aspects for deterministic E2E communication with 6G

It is the responsibility of WP1 to identify and define novel use cases that are enabled by E2E dependable time-critical communication within 6G wireless systems. Based on the analysis of different cyber-physical application domains, like extended reality (XR), occupational exoskeletons for human support and industrial automation, communication service requirements and key performance indicators (KPIs) are derived. Besides the well-known measures of KPIs, the new concept of key societal value indicators (KVIs) needs to be introduced and discussed in the context of the defined use cases. The findings of the use case analysis lay the foundations for the description of deterministic communication and computing services and the development of a formal service description language.

Other work packages take the results of the use case definition as a guidance for their corresponding actions. Conversely, those techniques enabling deterministic E2E communication, which are developed in these other work packages, flow back to WP1. Here they are integrated to build a holistic system architecture for deterministic E2E communication within converged 6G wireless and wired networks. Along with the definition of the DETERMINISTIC6G system architecture, a thorough security analysis of the architectural building blocks is conducted to identify vulnerabilities and mitigate their impact.

3.1 Achievements during the first year

The focus of the first set of activities for WP1 was on the definition of appropriate visionary use cases that clearly benefit from technological improvements which enable deterministic E2E communication in converged wired and 6G wireless networks. A set of industrial use cases has been identified, where an increasing demand for future applications is expected. In the following paragraphs, an overview of the use cases defined and detailed in deliverable D1.1 [DET23-D11] is provided:

Extended Reality (XR)

The term extended reality covers multiple immersive technologies that are capable of enriching the perceived environment with real or virtual components, for example, by using virtual reality head mounted devices. Due to the flexibility of this technology, it can be used in a huge range of verticals, like industry, health care, shopping, or manufacturing. The descriptions provided within DETERMINISTIC6G target at the usage of XR in the context of the industrial domain.

In this domain, XR technology can be applied, for instance, to support industrial workers during the training or maintenance by providing detailed instructions or information from remote trainers and experts. Virtual representations of factory floors and machines can be created, enriched with status and control information, which enables the most efficient operation by planners and operators even remotely. Furthermore, digital models can be shared among multiple XR users to foster collaborative design, and thus, optimizing the layout of factories and machines, or their processes and workflows.

On the one side, in order to create value for the user of the XR equipment, the augmentation of the environment must be performed in real-time. Otherwise, the user experience could be compromised, or in more advanced scenarios, users could be injured, or machines could be damaged. On the other side, depending on the complexity of the usage scenario, the augmentation process may require multiple computationally intensive tasks, that need to be offloaded from the mobile XR equipment for various reasons (e.g., to increase battery lifetime). While multiple XR applications can already be implemented on existing wireless technologies, fully immersive applications impose high requirements on communication bandwidth, latency and reliability that can only be achieved with a dependable wireless communication technology as targeted by DETERMINISTIC6G.

Exoskeletons in industrial context

An exoskeleton is a personal wearable equipment that physically supports a human to better perform physical activities. The applied assistance may either be passive by using a combination of springs, or active by using actuators and controllers. Also, semi-active implementations exist that combine both variants. There is a multitude of usage scenarios for exoskeletons, which includes medical and rehabilitation purposes or personal assistance and augmentation. However, the use case identified within DETERMINISTIC6G involves actively controlled occupational exoskeletons (OEs), which are used to reduce the physical burden of workers while performing physically demanding activities (see Figure 2).

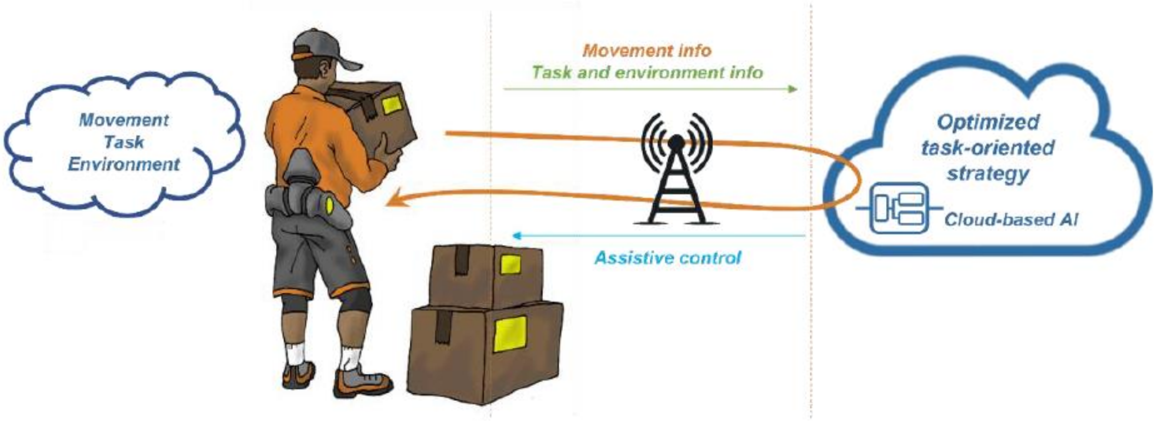


Figure 2 – Lumbar active OE use case

In this context, OEs can provide assistance to workers to reduce the biomechanical load on human muscles and articulations or allow them to handle heavy load reducing the physical effort of the user. Modern control and ICT technologies allow to optimally adapt the degree of assistance to the current task or workload. The automated detection of the currently performed tasks based on both, wearable or embedded sensors, and environmental sensors (e.g., cameras) comes with high computational efforts that need to be considered. Offloading these computations from the OE to the cloud reduces the weight of the onboard control and power electronics, increases the duration of the battery, and prevents negative effects of high thermal dissipation.

At the same time, the control mechanisms need to ensure the fulfillment of high safety requirements. Otherwise, the users may be impaired or even injured. Obviously, such control processes need to be performed in real-time, closing the loop of sensing, controlling, and actuating via the physical environment. In order to fulfill these requirements on the real-time control of OEs, dependable wireless communication is indispensable.

Factory automation: adaptive manufacturing

There is a strong trend in the industrial automation domain towards increased flexibility in industrial production systems. While the automation technology within machines is still dominated by wired networks, requirements for increased flexibility at the factory level – where multiple machines are integrated into a holistic production process – are more often satisfied by mobile transport and adaptive production systems.

Adaptive manufacturing integrates advanced technologies, like robotics, artificial intelligence, computer vision, track-based or planar product transport systems, or data analytics, to dynamically react to changes (e.g., in market demands or status of production systems) and optimize the production process accordingly. The focus of the use case descriptions for DETERMINISTIC6G was put on scenarios with vehicles autonomously driving in the shop floor and performing coordinated actions between each other or in combination with production cells. It is expected that such applications are highly integrated into future production processes, where humans and machines closely interact with each other (see Figure 3). Obviously, in such use cases, the highest safety standards must be applied, in order to prevent injuries and any damage to the machinery. This, in turn, requires dependable wireless real-time communication to close the control loops, which involve safety equipment, production cells and autonomous vehicles.

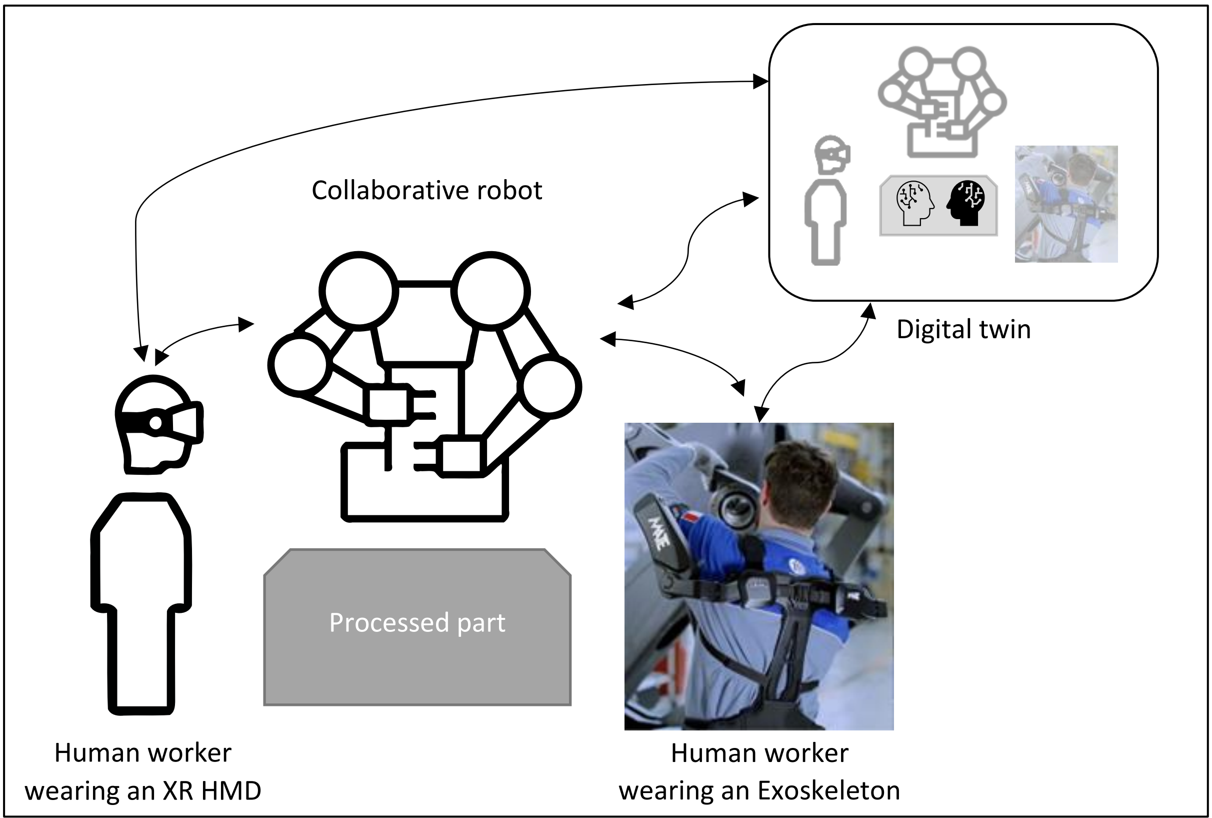


Figure 3 – Interactions within the combined use case scenario

Mobile automation: smart farming

The field of mobile automation includes many different subdomains, where automation technology is used in combination with mobile machines (e.g., excavators, harvesters, dumpers, drones, etc.). Examples for such subdomains are digital construction, mining, container terminal operations, or smart farming. In many of these applications, research and development target fully automated operations.

The smart farming use case was selected to be analyzed within DETERMINISTIC6G and to derive communication requirements from it. Also, within the smart farming domain a huge number of meaningful automation scenarios exist. The focus of the descriptions was set on communication relations between fully autonomous machines (e.g., harvesters, drones, trucks, etc.), where control loops are closed via mobile communication technologies.

The analysis of the corresponding communication requirements shows the need of E2E deterministic wireless communication in order to enable such use cases. In contrast to factory automation, the mobile automation use case additionally highlights the need for sophisticated network control and management planes, as the interacting machines might not always be under the governance of the same entity.

For each of the given use cases, communication relations have been defined and appropriate requirements have been derived. Moreover, a discussion was added to indicate the gap between the existing wireless communication technology and the features and properties that are required to implement the corresponding use case. Finally, to set the basis for the development and evaluation of cyber security mechanisms later in the project, a use case specific analysis of communication related security requirements has been conducted.

Learnings from Use Cases

The collected use cases clearly demonstrate the need of improved E2E dependability and determinism of communication in converged wireless and wired networks in order to be able to close control loops, ensure safe operations, achieve the requested level of user experience, etc. However, it can also be seen that not all the communication relations (i.e., data exchange activities between communication partners for a specific purpose) in a network do provide the same value to the user or system owner. This creates additional flexibility for the network control plane to react and prioritize certain communication relations (e.g., safety relevant communication) in case the desired deterministic behavior of the communication system cannot be ensured. In many cases, the application itself may also provide multiple options for accepted communication parameters (e.g., with different levels of requested bandwidth) such that the control plane is able to reduce the system load without the need to completely reject the requested communication relation. This way, the predicted behavior of the communication system can be kept within the desired bounds.

Key societal value indicators

Apart from the definition of functional and performance requirements, the relatively new concept of key values and key societal value indicators (KVIs) was elaborated in the context of the use cases. With the idea of KVIs, also the added value, which is brought by applications and use cases to the society and the environment, shall be evaluated and become measurable. Such indicators could, for instance, focus on the amount of saved resources or reduced emissions, the increase of well-being, the accessibility of goods or services (e.g., healthcare), or even on aspects of personal freedom. The discussions about KVIs turned out that applications typically come with different gains or losses for our society. However, in some cases it is even possible to relate these gains or losses with individual communication relations between networked devices. For instance, an application with high societal value might be enabled by the information exchange within the network (e.g., protection of wild animals by letting a drone observe the area ahead of a farming machine). Beside the general discussion on the KVI concept, it is in the interest of DETERMINISTIC6G to identify especially cases that are traceable to communication within 6G systems, to enable the maximization of societal gains and minimization of societal losses.

Security aspects

When designing the architecture of modern ICT systems, it is indispensable to consider security aspects from the beginning. Also, for the DETERMINISTIC6G architecture cyber security is of highest importance. Especially, because adding novel control facilities and mechanisms for system monitoring may open new vulnerabilities to the system architecture. The actual security analysis and development of means for protection need to be done along with the design of new architectural concepts and their implementation. However, as a starting point for the security related work in other work packages, the principles of the security assessment and security requirements concerning deterministic networking have been elaborated in deliverable D1.1.

Compute service requirements

Since the E2E performance of applications usually depends on the interplay of communication and computation activities, also the computing resource requirements have been discussed and documented in deliverable D1.1. Cyber-physical systems typically consist of sensors and actuators that interact with the physical environment. The control loop is realized by implementing a control algorithm between these sensors and actuators, where the trend goes into the usage of Cloud services. The overall quality of this control loop heavily depends on the E2E latency from sensing to actuating, which includes the computational part with the control logic in between. The best performance is achieved when there is spatial proximity and a perfect temporal alignment of the communicational and computational resources. This means that the communication and computation paths with the lowest latencies shall be selected, and computation and communication are scheduled in a way that the guaranteed E2E latency is minimal. Thus, it is important that there is a precise description of computational service requirements that can be included in the (automated) scheduling decisions. As one step towards this goal, a first analysis of use case related computing resource requirements has been conducted.

6G Architecture for time-sensitive and deterministic services

The 5G system architecture for support of TSN and DetNet is taken as a baseline for further developing an architecture towards 6G. A thorough review of the 5G architectural design has been made for support of time-sensitive and deterministic services. Based on this, new architectural aspects have been identified that should be included in a 6G system architecture. One aspect is that more emphasis needs to be put onto providing *dependable communication* for time-critical services with 6G.

Dependable communication implies, that the application can clearly specify its requirements, and the 6G system must be able to monitor and evaluate the delivered performance, so that the delivery of the expected service performance and reliability can be confirmed or proven. On one hand, the network should allow applications to specify their needs and requirements. This is even more important as applications are developing towards larger flexibility, including dynamic adaptations of operation modes and requirements. To this end, better provide better programmability of the network should be possible, for example via network exposure. On the other hand, better observability of the service performance is needed, as well as the capability to predict service performance into the future. For the latter a data-driven approach is envisaged that builds on ML-based prediction, and it requires an architecture that caters for including network probes and data collection for the service performance prediction. In addition, in order to meet requirements on high reliability and availability, a future 6G architecture shall provide capabilities for network reliability, availability, and resilience; this includes a design avoiding single-points-of-failures and minimizing dependencies on functional operation, e.g., between the control plane and the user plane functions of the network. It also includes a principle of security-by-design to monitor, analyse, prohibit, and mitigate security threats.

3.2 Next steps

The next steps consist of further developing the DETERMINISTIC6G architecture in close interaction with other work packages. Technologies enabling dependable and predictable communication in 6G systems, as well as enablers for convergence of 6G wireless communication with deterministic wired communication, need to be integrated into a holistic architectural view. The value of individual enablers to achieve the overall objective of E2E deterministic communication will be elaborated and summarized in the next deliverables. One part of this elaborations and reporting will be thorough cyber security discussions and evaluations for the whole architecture.

Furthermore, a comprehensive concept for a deterministic service definition will be worked out. This service definition will be built on the findings of the previous use case descriptions and shall include relevant KPIs, as well as some relevant notions of the KVI concepts. Based on these service descriptions, applications may formulate their requirements on communication and computation using a defined interface. A system implementing the DETERMINISTIC6G architectural concepts may then monitor the predicted system performance and provide appropriate reactions (e.g., changing configurations or reduction of scheduled communication system load) in case the predicted behavior deviates from the intended stable behavior.

4 6G centric enablers for deterministic communication

The activities in WP2 are intended to enable deterministic capabilities for the 6G system such that it can offer the required service. We have identified that characterizing and controlling the 6G packet delay and that time synchronization enhancements to cover for future needs are key. More specifically, the objectives of this work package are threefold: (i) development of concepts to achieve deterministic communication in 6G, where the packet delay variation (PDV) through the 6G system can be bounded to a range of 10's of microseconds, (ii) data-driven latency characterization of the 6G wireless network applying machine-learning and inference to estimate the stochastic behavior of latency, and (iii) development of an E2E time synchronization solution to satisfy the need for the deterministic communication services of proposed use cases. To achieve these three objectives, WP2 is divided in three tasks: task 2.1 handles objective (i), task 2.2 handles objective (ii), and task 2.3 handles objective (iii). The per-task progress is described in the next section.

4.1 Achievements during the first year

During the first year, two technical reports were produced. The deliverable D2.1 [DET23-D21] elaborates on latency analysis in 6G transmission, concepts for reducing packet delay variation, RAN resource allocation concepts and challenges, as well as deep neural network-based mixture models combined with extreme value theory for the conditional density estimation of latency. D2.1 involved the outcome of activities in tasks 2.1 and 2.2.

The deliverable D2.2 [DET23-D22] provides details on the initial enhancement proposed for the time synchronization mechanism for the 6G architecture. D2.2 included the work in task 2.3.

4.1.1 D2.1 – First report on 6G centric enablers

Task 2.1

Wireless transmission has by its nature properties that introduce variable latency components. An analysis of the 6G latency components was included in this first report, leading to the conclusion that corrective mechanisms with no spectral impact or higher cost are required. To achieve that, novel concepts were proposed to achieve deterministic transmission in 6G by controlling the packet delay variation such that all packet transmissions happen within a narrow latency window. One solution for packet delay correction (PDC) is based on the use of timestamps. As shown in Figure 4, the idea is to hold the packet for some time (to correct the packet delay) in an egress port queue such that all TSN packets experience approximately the same delay (predefined delay limit) within the 6G system. Using a PDC based on timestamps allows to know how long the packet has spent within the 6G system, and when it is time to forward this packet based on the predefined delay limit. This predefined limit can as well be two numbers, maximum and minimum limits, which difference corresponds to the objective level of PDV. The PDV should be as close to zero as possible. PDC is a method to compensate for the PDV that intrinsically happen in the 6G system.

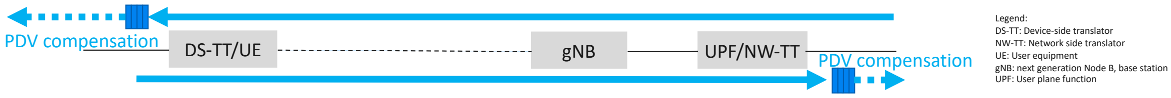


Figure 4 - Packet delay correction (PDC) to compensate for packet delay variations (PDV)

Timestamping-based PDCs include solving additional issues such as: (i) using a pseudo-timestamp in order to avoid the challenge of wire-speed timestamping, (ii) generalizing the proposal of pseudo-timestamping to any type of communication, and (iii) how to transfer such pseudo-timestamp in the packet through the 6G system. Another solution for PDC is based on number of radio retransmissions corresponding to a packet, requiring that the packet transports such metadata and using a cyclic queueing and forwarding (CQF) queue mechanism for the delay correction. As a result, the larger the number of retransmissions the less the packet will be enqueued in this CQF queue, and the lower the retransmission the more the packet will stay enqueued. The objective is that all TSN packets spend approximately the same time in the 6G system (i.e., lowering the PDV).

While Radio Access Network (RAN) retransmissions methods are critical for enhancing reliability and reducing latency, there is a need for solutions to streamline the repetitions and retransmission processes. This includes reducing retransmission delays, minimizing resource utilization, and optimizing the retransmission strategy for different types of applications. This can be achieved via the design of RAN resource allocation mechanisms, which in this task initially considered the handling of XR traffic. The investigation into the scheduling of traffic considering repetition and re-transmission schemes has yielded to the challenge of optimizing network performance while balancing the quality of service provided to users with efficient resource utilization. This involves trade-offs between reliability, latency, data rates, and network capacity. This will require the development of adaptive and intelligent network management strategies.

Task 2.2

In addition to the system enhancements targeted to reduce stochastic uncertainties impacting transmission latencies in 6G, further enablers will be required to support end-to-end dependable time-critical communications. Accurate predictions of stochastic characteristics of evolving conditions of the 6G system can enable adjustments in the system and/or application such that required application performance levels can be maintained. To this end, data-driven approaches for latency characterization in 5G-Adv/6G are also proposed and described. The proposed approach is the development of deep neural network-based, also referred to as mixture density networks (MDNs), leveraging extreme value theory. The goal here is to build conditional density estimators which outperform state-of-the-art estimators significantly, especially in estimating tail latency. This is achieved by leveraging generalized pareto distributions (GPDs) for tail modelling, together with Gaussian distributions for the bulk of distributions. The accuracy of the proposed estimators is evaluated using data collected on a commercial off-the-shelf (COTS) 5G setup and an OpenAirInterface (OAI) based software-defined radio (SDR) 5G setup. The evaluations showed that GPD-based MDNs leveraging (GMEVM) outperforms generic MDNs (GMM) even with smaller number of training samples (see Figure 5).

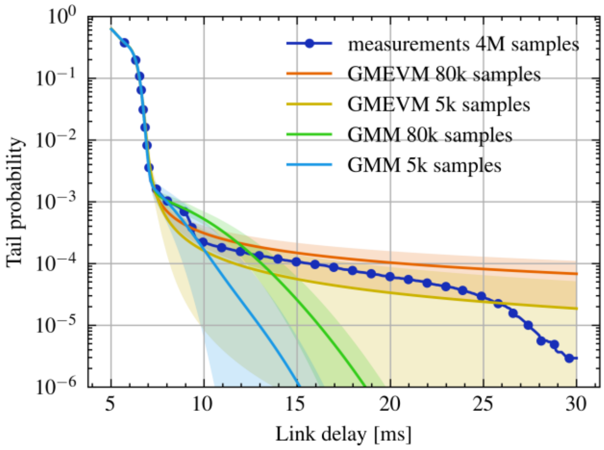


Figure 5 – COTS 5G uplink latency empirical distribution (blue) vs predicted distributions for different number of training samples and models.

4.1.2 D2.2 - First report on time synchronization for E2E time awareness

Task 2.3

This deliverable included a discussion of time synchronization industrial use cases, thereby illustrating the multifaceted applications of precise timing coordination within the realm of industrial automation. This report introduced the present issues that require new mechanisms to improve time synchronization in mobile communications for better integration with fixed TSN networks. For time synchronization resiliency, the IEEE P802.1ASdm – Hot standby amendment is used as the focal point to minimize network synchronization discontinuity by maintaining time domains from both the primary and secondary clocks. Figure 6 shows a model of the 6G virtual TSN bridge connected to a TSN network with end-to-end time synchronization distribution that supports the hot standby mechanism. As a result, when the primary clock fails, the secondary (hot standby) clock will take over immediately without any disruption in the time synchronization distribution. Security aspects are also considered by proposing the integration of monitoring, threat, and vulnerability assessment and countermeasures to guarantee reliability and robustness of the system.

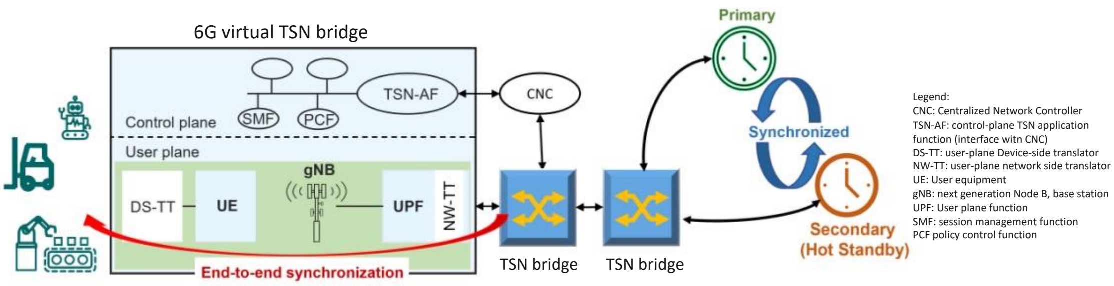


Figure 6 – End-to-end synchronization using reliable hot standby (IEEE P802.1ASdm, hot standby amendment)

4.2 Next steps

As a next step regarding PDC, the proposed mechanisms will be evaluated via simulations in the context of end-to-end dependable communications. As a future work, advanced latency prediction methods utilizing recurrent neural networks will be investigated to predict time-dependencies. Architectures for ML-based latency prediction in 6G systems will be further investigated, while trying to optimize for prediction accuracy and low system impact.

On RAN resource allocation, several avenues will be researched considering adaptive repetition schemes, Machine Learning (ML) integration, energy efficiency, and user experience. The aim will be to further understand and implement the k-repetitions for data transmission reliability.

For the case of time synchronization for E2E time awareness, more refined mechanisms for enhancing the time synchronization reliability in the 6G architecture will be proposed and evaluated. Proposed security mechanisms for time synchronization mechanisms will also be evaluated.

5 Enablers for 6G convergence with deterministic communication

The work on enablers for 6G convergence with deterministic communication is to analyze how wired deterministic communication solutions, such as TSN and DetNet can be integrated with 6G mobile networks. The main goal is to look into the mechanisms to enable resource-efficient and optimized end-to-end communication for deterministic communications integrating 6G mobile systems. Moreover, we identify how deterministic communication can be supported in an edge cloud environment and still fulfil the TSN requirements. Security needs to be part of resilience networks, hence the architecture for deterministic communication with in-built security is also defined.

The work on enablers for 6G convergence with deterministic communication has been separated into four different tasks to focus the activities around the following main areas; Task 3.1) Identify wireless friendly system design, Task 3.2) Edge cloud solutions for deterministic services, Task 3.3) Security framework and Task 3.4) Digital Twin usage for prediction.

5.1 Achievements during the first year

In the following sub-sections, the overview of the achievements for each of the tasks during the first year of the project is provided. Some more technical details can be found regarding D3.1 [DET23-D31], which covers the results related to 6G convergence with deterministic communication and D3.2 [DET23-D32], which presents the proposed security framework.

5.1.1 Task 3.1: Wireless-friendly design of end-to-end deterministic communication

In the first task related to wireless friendly interface, a list of parameters that affect traffic scheduling were identified. Initial analysis of the interface to deliver these parameters to wireless friendly Centralized Network Controller (CNC) was discussed and standard 3GPP network functions such as Network Data Analytics Function (NWDAF) and Network Exposure Function (NEF) were listed for implementing such interfaces. In this task the major contribution is included in Deliverable D3.1 [DET23-D31].

Deliverable D3.1: Report on 6G convergence enablers towards deterministic communication standards

The deliverable D3.1 provides details on wired and wireless deterministic communication standardization efforts that will serve as enablers of 6G convergence for E2E deterministic communication. A scenario where one side of the deterministic communication is located in the cloud system, integrated with the wireless network, is shown in Figure 7. Many open questions and specification gaps on TSN/DetNet interfacing with 6G wireless nodes, configuration protocols, 6G network exposure capabilities, and information exchange between the wired and wireless domains, regarding seamless integration and E2E deterministic communication support, are highlighted. Additionally, support of Resource Allocation Protocol (RAP) for integration of TSN with distributed configuration in heterogenous environments, i.e., with wired and wireless domains, has been explored. Moreover, the report highlights that the enhancements or detailed interactions of existing 5G functionalities such as the Time Sensitive Communication and Time Synchronization Function (TSCTSF) for control/management plane communication need to be described further for 6G systems.

Furthermore, details on traffic shaping concepts and E2E scheduling algorithms are also discussed. Traffic scheduling algorithms are needed to guarantee E2E bounded delay. It is to note that the propagation, processing, and transmission delays are accommodated as a part of the E2E schedules. However, PDVs have not been considered so far in scheduling algorithms. Therefore, novel wireless-friendly scheduling approaches are required to be reactive to dynamic PDVs to guarantee E2E bounded delays. Potential scheduling approaches that consider PDVs and can still provide robustness and reliability are discussed in detail.

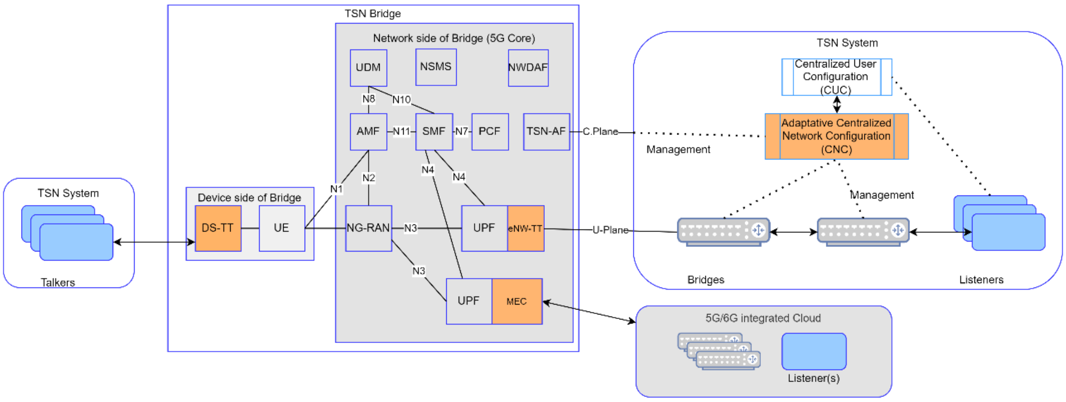


Figure 7 – 5G/6G is combined with cloudification of the deterministic TSN application

5.1.2 Task 3.2: Edge cloud solutions for deterministic communication services

The activities related to edge computing are grouped into two major areas, namely the investigation of architectural aspects for the integration of 3GPP TSN and edge computing support, as well as the development of concepts for enabling the tight integration of the networking in the cloud virtualized domain and in the TSN domains. In both tracks the main assumption is that, by leveraging the technique of virtualization, some real-time application components are offloaded from the device or a dedicated hardware to the compute domain, e.g., to an edge cloud deployment.

In the architecture track one goal was to conduct a gap analysis for a deployment scenario, where the 5G/6G network domain is integrated to a TSN deployment as a virtual TSN bridge, and at the same time, the application – serving as TSN endpoint – is deployed in an Edge computing environment. The intention was to identify missing features of this scenario and propose an initial sketch for the architecture integration. As part of this activity, the first implementation of 3GPP Rel 17 architecture for Multi-Access Edge computing (MEC) was completed. During the first period, the MEC implementation was used to run performance measurements, including commercial devices, and integrating O-RAN base station and other commercial base stations.

In another track the main problem to be addressed arises from the uncertainties in scheduling and timing of the applications in the virtualized execution environment. If the TSN 802.1Qbv scheduled traffic concept is used in the TSN domain, the applications deployed in the compute domain must generate traffic according to the calculated 802.1Qbv schedule. Since currently there is no solution that can ensure Qbv-aware traffic handling in the virtualized domain, the major focus in the first year was to propose a conceptual solution for this problem. A framework is described, which consists of the time-aware configuration of the virtual interfaces of the containers and a time-aware queuing scheme in the container networking domain. The framework can ensure the required traffic shaping and frame ordering in the virtualized network domain resulting in the frames arriving to the NIC physical queues of a server node according to the configured 802.1Qbv schedule.

5.1.3 Task 3.3: Security by design architecture and framework

In this track, the state-of-the-art analysis of security threats, vulnerabilities and techniques were performed, and an initial description and implementation of the tool to monitor and detect the security breaches was identified. The major contributions of this task resulted in Deliverable D3.2 [DET23-D32] that consisted in a report and the delivery of the first version of the monitoring framework addressing the detection of security anomalies in dependable time-critical networking. The high-level architecture of the framework is presented in Figure 8. The figure shows the closed loop security management represented by the steps 1 to 5.

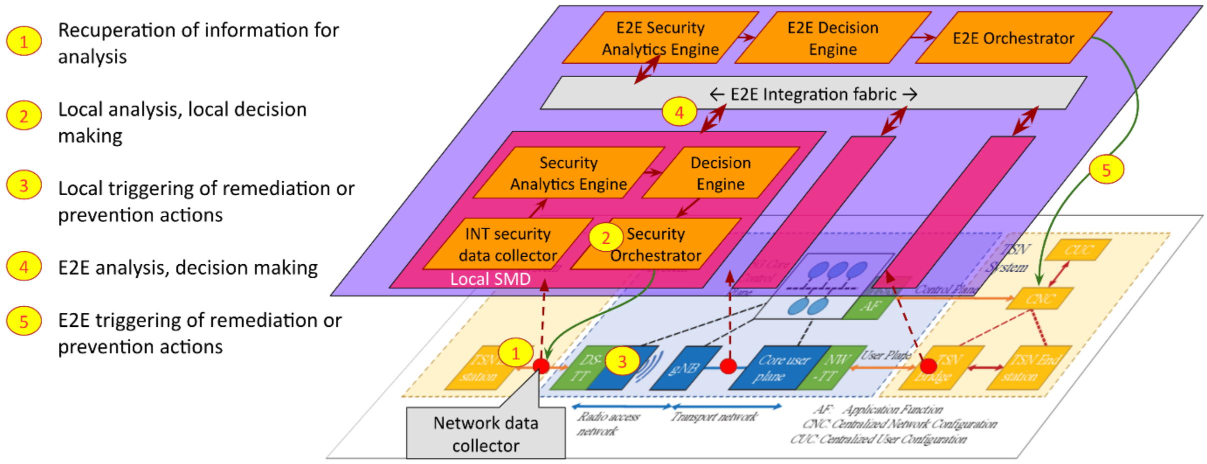


Figure 8 – High level architecture of E2E security monitoring and management framework

Deliverable D3.2: Report on the Security solutions

This deliverable consists of a software solution for monitoring and analyzing security threats related to deterministic networking within 6G networks and TSN and DetNet networks. The software release is accompanied by a report that includes a description of the context (requirements, state-of-the-art, standards, and techniques), and a vulnerability and threat analysis that can affect TSN and DetNet networks leading to malfunctions and disruptions.

This deliverable outlines the security monitoring framework developed for the DETERMINISTIC6G project, offering a detailed analysis of deterministic networks and advanced security monitoring techniques. It corresponds to a unique innovation in that it offers an open-source solution for fine-grained analysis of deterministic communications to detect security-related disruptions. It highlights the core challenges, standards, and security-by-design principles crucial for protecting deterministic networks. Now in its initial release, this framework is tailored to bolster the resilience of the DETERMINISTIC6G system, particularly in end-to-end scenarios, and is aligned with the 3GPP Zero-touch Services Management (ZSM) model to meet evolving security needs. The framework employs AI/ML algorithms for proactive threat detection and leverages In-band Network Telemetry (INT) and P4-based programmable data planes for providing the flexibility required by different applications and the immediate enforcement of security policies. Designed for dynamic adaptation, it can rapidly adjust to new threats, ensuring precise and flexible security management in the complex environment of wireless, virtualized, and edge-driven networks, particularly in applications requiring low-latency and deterministic responses.

5.1.4 Task 3.4: Situational awareness via digital twining

This task addressed situational awareness via digital twining through three major parts. The first one focused on analyzing the usability and benefits of situational awareness within the scope of novel use cases covered in WP1. Through the analysis of use case dynamics and communication requirements, critical operation points that could impair the network performance were identified and used to determine the situational information that network digital twin (DT) could provide to mitigate the degradation of the communication QoS. This led to the necessary set of parameters the network DT would need to accurately predict critical scenarios and generate preventive measures for the network and CPS.

The second part covered the state-of-the-art of DT concepts in the scope of CPS and mobile networks. The focus was on modeling of DT, DT lifecycle, DT deployment, and application areas. Literature shows that significant advancements in AI technologies, cloud computing, and IoT have resulted in the deployment of DT applications in manufacturing, aviation, healthcare, and other industries. From the 6G perspective, 6G is seen as an enabler of mass usage of DT technologies in the industry but also DT could facilitate 6G network deployment and design and provide high network resilience.

The third part addressed the data exchange between CPS DT and network DT for parametrization of network DT and delivering situational information as it is shown in Figure 9.

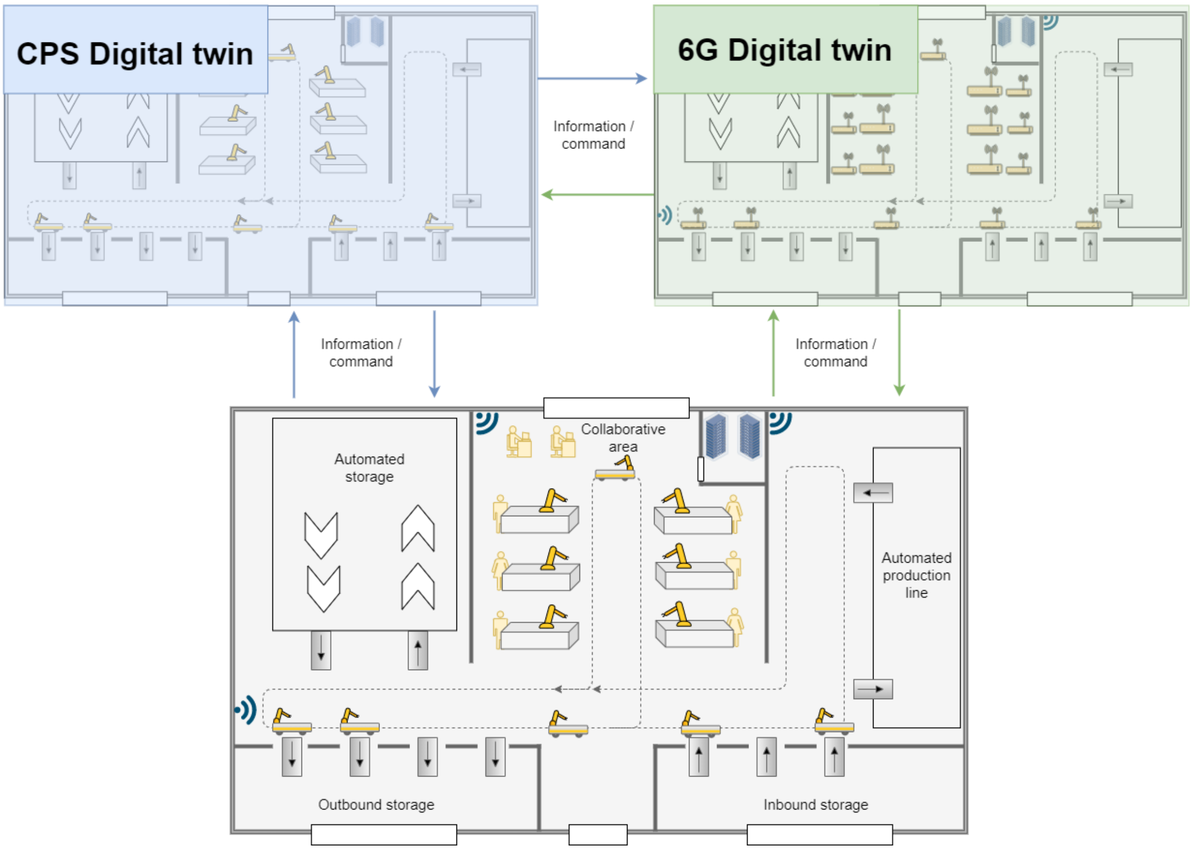


Figure 9 – Illustration of interaction between CPS digital twin and 6G digital twin

Analysis of critical points of use cases in the first part showed that network DT would most likely require parameters from the network domain but also from the CPS domain. Similarly, situational information and action measures generated by network DT could be applied on the network itself or delegated to CPS through CPS DT. Therefore, state-of-the-art 5G architecture was taken as a starting point to tackle the data exchange requirements between operational systems and their DT counterparts. Specifically, the 5G Network Data and Analytics Function (NWDAF) was considered a central data collection hub. However, due to the amount of data DTs would need, it was not concluded that NWDAF is a suitable solution, but further research is needed on this area.

5.2 Next steps

The work on each different task will be continued by the end of the project with the following targets:

Task 3.1: The main target is to design the interfaces with the required parameters to deliver a wireless friendly interface towards fixed TSN controllers. This task will analyze different algorithms that will improve TSN integration of 6G system with fixed TSN networks. Moreover, this task will contribute to WP4 for the simulation and validation of the selected algorithms. Interaction with WP2 is expected in order to take into consideration PDC mechanisms for the scheduling algorithms. The functionality extension for 6G virtual bridge with integrated RAP will also be considered as part of the future work.

Task 3.2: In this task the next step is to evaluate the usage of MEC as part of TSN bridge and will continue and identify which additional parameters would be required to the wireless friendly interface to reflect the usage of MEC. The architecture principles for the integration of TSN control plane and the cloud management plane to support the deployment of cloudified applications will also be investigated.

Task 3.3: The security work will continue with the analysis of vulnerabilities and threats to TSN networks and plan the evaluation of the tools for detecting and mitigating those vulnerabilities. It will integrate AI/ML-based analysis for the detection, identification of the root causes, and response; propose dynamic and automated security management based on closed-loop security; and elaborate an end-to-end security architecture and deployment for the protection of scheduling and multi-domain environments.

Task 3.4: This task will continue with the focus on defining the necessary information for accurate prediction of increasing probabilities of communication failures. Further on, the improvement of latency-driven predictions through the interaction of CPS DT and 6G DT will be investigated. Finally, this task will identify network functions and architecture changes required to support 6G DT and will contribute to WP1 on the architecture design.

6 6G deterministic communication validation framework

The purpose of the validation framework is to validate the concepts designed in WP2 (*6G Centric Enablers for Deterministic Communication – Section 4*) and WP3 (*Enablers of 6G Convergence for Deterministic Communication – Section 5*). The validation scenarios are driven by the use cases developed in WP1 (*Vision, Architecture and System aspects for Deterministic E2E Communication with 6G – Section 3*).

The validation framework consists of a network simulator based on the OMNeT++ simulation framework and INET library for network simulation. In particular, the simulator is able to simulate the characteristic packet delay and packet delay variation (PDV) of wireless 5G/6G networks to evaluate its impact onto essential mechanisms such as time-driven scheduling as defined for Time-Sensitive Networking (TSN) in IEEE 802.1Qbv or time synchronization with the Precision Time Protocol (PTP). To facilitate realistic simulation results, data from a wireless testbed is translated to simulation models to implement a data-driven simulation approach based on measured delay data.

Besides the network data plane with its characteristic PDV, also applications and services hosted in an edge cloud environment are simulated, in particular, with respect to their impact onto end-to-end network delay.

The work carried out in WP4 is split into the following tasks, whose achievements will be described below:

- Task 4.1: Simulation Models for the Data and Control Plane – This task is focusing on the simulation of the network data plane, in particular, including its characteristic PDV.
- Task 4.2: Simulation Models and Experiments for the Edge Cloud, Security, and Applications – This task focuses on the simulation of applications and services hosted in an edge cloud, in particular, including their impact onto the end-to-end delay.
- Task 4.3: Data-driven Analysis for RAN Latency Inference – This task focuses on delay measurements in a wireless 5G testbed to drive the data-driven simulation with realistic delay data.
- Task 4.4: Concept Evaluation via Simulations – This task focuses on producing the validation results using the validation framework designed in Task 4.1 – Task 4.3.

6.1 Achievements during the first year

In the following sub-sections, we provide an overview of the achievements for each of the tasks for the first year, before we describe future work in WP4 in the sub-sequent sub-section. More technical details about the simulation framework can be found in deliverable D4.1 *DetCom Simulator Framework Release 1* [DET23-D41].

6.1.1 Task 4.1: Simulation Models for the Data and Control Plane

The simulation models for the network data plane should enable the realistic simulation of TSN networks with wired TSN bridges and wireless TSN bridges, also called 6G DetCom nodes in the following. One essential property of 6G DetCom nodes is their higher PDV when forwarding packets over wireless links, compared to the relatively small PDV of wired TSN bridges.

Therefore, the main focus in the first year was to extend the existing TSN simulation models of the INET framework for wired TSN bridges with the ability to simulate the characteristic PDV of wireless 6GDetCom nodes. To this end, the data plane models of wired TSN bridges have been extended by a so-called Delayer component that adds PDV to forwarded packets. A generic approach has been implemented that enables to specify different delay distributions individually per port-pair and uplink/downlink directions. Moreover, the design is generic in the sense that it allows for specifying delay as closed-form formula (probability distribution), algorithmically as implementation of a stochastic process, or through direct integration of delay data sets as histograms as provided by Task 4.3 (cf. Section 6.1.3). Figure 10 shows where the delay is added conceptually in the data path (a more technical architecture showing the implemented sub-components is available in [DET23-D41]). After entering the 6G DetCom node through the ingress interface – e.g., through a UE –, the Delayer adds delay before enqueuing the packet into the egress queue of the TSN bridge, before they are scheduled by the Time-Aware Shaper (Qbv) in this figure. This approach allows for re-using all existing TSN features implemented by INET, such as the different TSN shaping mechanisms, such that the 6GDetCom nodes behaves as a wireless TSN bridge. Figure 11 shows a given delay distribution for configuring the 6GDetCom node, and the corresponding PDV as simulated by the framework.

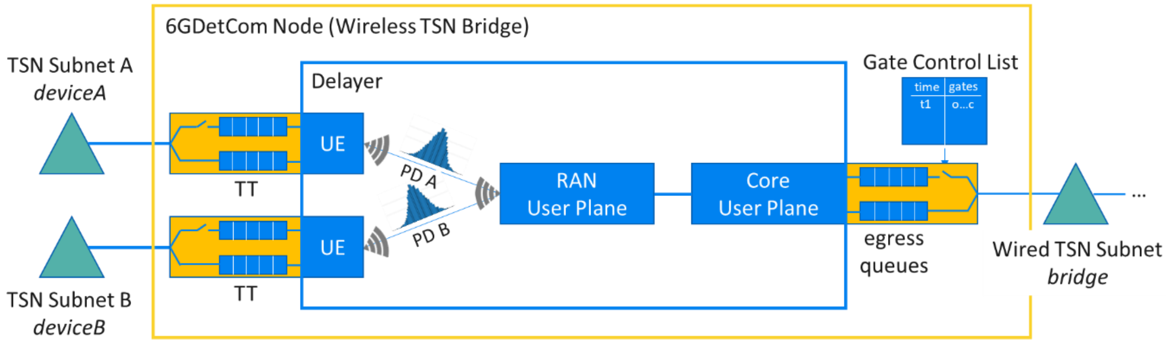
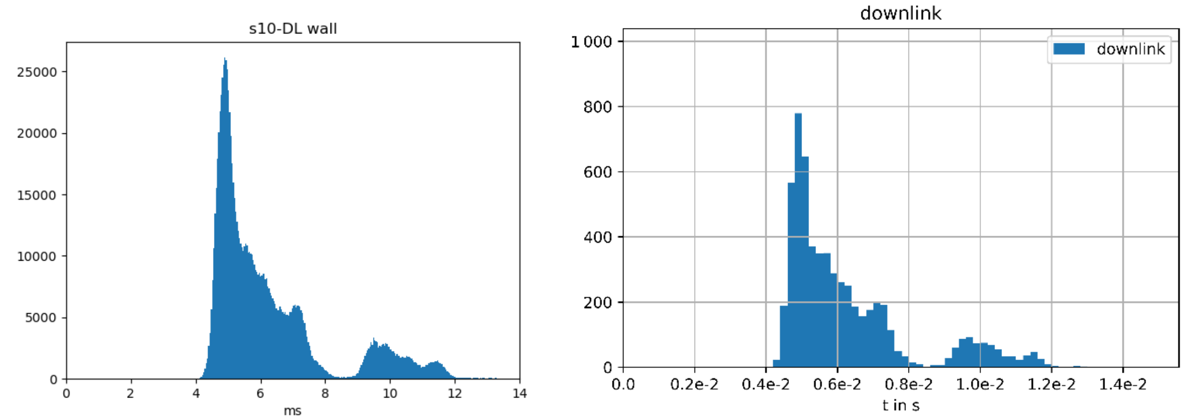


Figure 10 - 6GDetCom node with two wireless TSN subnetworks and a delayer component.



Error! Reference source not found.11a: Input distribution

Error! Reference source not found.11b: Resulting distribution

Figure 11 - Comparison of input distribution and the distribution of the simulation results.

Besides the functionality to simulate PDV in the data path, also different exemplary models of PDV have been added, including models based on measurements with a wired TSN bridge as well as different models measured with wireless 5G nodes (for more details about wireless PDV measurements, see Section 6.1.3).

With respect to control plane simulation models, which are responsible for configuring the data plane mechanisms such as shaping, the focus was on simple static configurations, basically through configuration files defined prior to the start of the simulation. For instance, to specify the PDV of 6GDetCom nodes. Despite its simplicity, the configuration through configuration files still allows for changing PDVs at pre-defined points in time during the simulation.

6.1.2 Task 4.2: Simulation Models and Experiments for the Edge Cloud, Security, and Applications

Besides network delay, end-to-end delay also includes processing delay of applications. In particular, processing delay is crucial for applications including a full “loop” from end systems to edge cloud applications and back to end systems, like in a networked control system: transmission of sensor values from sensors to the edge cloud application implementing the controller; transmission of actuator commands from the edge cloud application to actuators. To validate such advanced scenarios with edge cloud applications, also the processing delay of such applications has to be simulated.

To model processing delay of applications, a similar data-driven approach as for simulating network delay is used. Instead of simulating the complete edge cloud environment and application – which is a very complex task since it would require to simulate the effects of multiple layers of virtualization, processing hardware, application logic, etc., we integrate processing delay models stemming from measurements into the simulation. Similar to packet delay variation, our implementation supports modeling processing delay as closed formulas (probability distributions), through data sets (histograms), or algorithmically for modelling stochastic processes.

We also extended the INET application model to add processing delay after receiving an incoming message (e.g., sensor values) and before sending an outgoing message (e.g., actuator commands).

Besides the implementation of the simulator, we also provide exemplary delay models (data sets) measured in an edge cloud environment.

6.1.3 Task 4.3: Data-Driven Analysis for RAN Latency Interference

The need for precise latency measurement in the DETERMINISTIC6G project arises from two crucial requirements. Firstly, latency measurement data is important for the development of representative simulation models of 6GDetCom nodes. In particular, delay distributions corresponding to different port-pairs and directions (Uplink and Downlink) of a 6GDetCom node can be obtained using latency measurements. Secondly, latency measurement data is indispensable for realizing data-driven latency prediction models. The collected latency measurement data is used to not only train latency predictors but also validate and test them.

In the first measurement campaign, our setup consisted of two nodes and a private COTS 5G. One node is connected to a COTS User Equipment (UE) and the other connected to the core network of 5G. Tight time synchronization in the measurement setup is realized using Precision Time Protocol (PTP) message exchanges happening on a dedicated network interface of each node. The campaign involved separate measurements for both uplink and downlink directions, with packets transmitted from the source to the destination at fixed time intervals. At the source and destination application instances, packets were timestamped in addition to capturing crucial network conditions, including position, Reference Signal Received Power (RSRP), and Reference Signal Received Quality (RSRQ). Multiple measurement rounds were conducted, each corresponding to different packet intervals and payload sizes, providing a comprehensive dataset for diverse scenarios. Throughout each measurement round of the campaign, one million latency samples were meticulously collected. The ongoing work in this task is focused on building a 5G setup using OpenAirInterface and leveraging Software-defined Radios deployed in the testbed. The distinctive advantage of employing such a setup instead of the COTS 5G setup lies in its capability to insert measurement points within the 3GPP 5G stack on both the UE and gNB (Next-Generation NodeB) sides. This placement of measurement points allows for the timestamping of packets as they reach these designated points. Furthermore, this timestamping process captures important metadata, including details such as Transport Block Size (TBS), HARQ (Hybrid Automatic Repeat Request) rounds, etc. This approach enhances the granularity of our measurements and provides deeper insights into the performance of the 5G setup under investigation.

6.1.4 Task 4.4: Concept Evaluation via Simulations

The concept evaluation is based on the implementation of different scenarios for the simulation framework. A simulation scenario defines a concrete network topology including network elements such as bridges and applications acting as talkers and listeners and their traffic specifications. Different configurations can be evaluated and compared such as the performance of "wireless-friendly" time-aware schedules for IEEE 802.1Qbv (Time-Aware Shaper) vs. standard schedules as calculated for wired TSN networks, or the performance of time-synchronization with gPTP with different PDV distributions.

For the first release of the simulation framework, the following scenarios have been defined:

- Baseline scenario: a simple line topology with wired and wireless bridges (6GDetCom node). Despite its simplicity, this scenario can be used to test the new features of the simulation framework such as adding packet delay (PDV) or processing delay in applications on end-systems.
- Industrial scenario: This more sophisticated scenario is based on a use case from WP1 (cf. deliverable D1.1 DETERMINISTIC6G use cases and architecture principles [DET23-D11]). It contains two mobile Autonomous Guided Vehicles (AGV), which communicate via wireless links of a 6GDetCom node with a processing cell.
- Scenario for time synchronization. This scenario allows for evaluating the performance of time synchronization with gPTP with different PDVs and (later) the performance of advanced concepts such as hot standby time servers.

As a first preliminary evaluation result, the impact of PDV onto time-aware shaping (IEEE 802.1Qbv) has been evaluated, comparing a standard algorithm for calculating gate control lists against a wireless-friendly scheduling approach, which we present in the following briefly as one example how the validation framework can help to evaluate concepts developed in the project. We simulated the end-to-end delay of two streams sharing common links for different scheduling approaches (standard scheduling vs. wireless-friendly scheduling). In particular, we added delay with PDV to links. Figure 12a and Figure 12b show the end-to-end delay over time for the standard scheduling approach and wireless-friendly scheduling approach, respectively. Without going into detail, we can clearly see that the wireless-friendly schedule leads to smaller delay than the standard approach for both streams. Also, the stochastic character of end-to-end delay due to PDV becomes visible. This shows that the simulator can serve as a tool for validating scheduling approaches and particularly the influence of PDV onto scheduling and – as part of future work – also on other concepts subject to investigation in the project such as time synchronization.

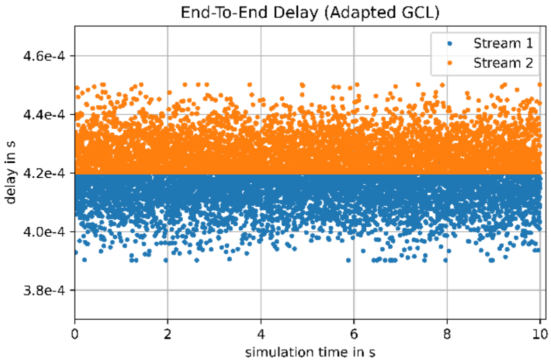


Figure 12a – Resulting end-to-end delay using the standard scheduling approach.

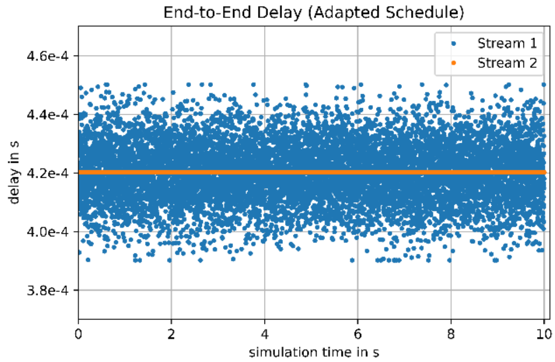


Figure 10b – Resulting end-to-end delay using a wireless-friendly scheduling approach.

Figure12 - Effect of PDVs on different scheduling algorithms.

6.2 Next steps

The simulation framework will be further extended along different directions:

While the focus of the first release was on the data plane simulation models, the next release will also include control plane features to simulate dynamic scenarios and the adaptation to dynamic environments. For instance, the dynamic adaptation of schedules through algorithms executed by a Centralized Network Controller (CNC) will be integrated. This also requires the simulation of an event-driven adaptation mechanism, where the CNC reacts to events from the data plane or via digital twins to environmental changes.

Moreover, further delay models from a wireless testbed will be integrated.

Security-by-design architecture will be detailed, and the security mechanisms will be further developed and integrated in the simulator to be evaluated.

Also, the scenarios will be extended and refined, e.g., to evaluate hot standby mechanisms for gPTP, advanced scheduling mechanisms, security mechanisms, or dynamic scenarios with mobility.

Finally, the simulation framework will be used extensively to produce results to validate and evaluate the different mechanisms from WP2 and WP3 that are designed concurrently with the simulation framework.

7 Dissemination and impact

The objective of the impact and dissemination work package is to ensure that the project results are properly disseminated and are made available to relevant stakeholders including the industry, standardization bodies, academic and research community, and to a wider audience in general to maximize the impacts of the project. In this respect, a deliverable report D5.1 [DET23-D51] on DETERMINISTIC6G impact and dissemination plan titled "Impact, exploitation, and dissemination plan for academic research, awareness of potential benefits to industry, standardization synergies" has been prepared and is available on the project’s webpage. The report details available tools and channels for dissemination, planned communication and dissemination activities, and actions to achieve the exploitation objectives of the project. The report is available on the project website. The following sections provide details on the dissemination, communication, and standardization activities that have been carried out so far.

7.1 Dissemination and public communication

The communication and dissemination activities aim to promote the project results and outcomes to a wider audience. The widespread knowledge sharing of the research activities performed under the project will help to support the adoption of the project results and ideas at various standardization bodies, industrial organizations, and SMEs. Moreover, public awareness on technological advancements and targeted application scenarios is planned. This section explains the communication and dissemination activities performed during the first year to promote the outcomes of the project.

As the DETERMINISTIC6G aims to define and develop new fundamental concepts for 6G deterministic communication technology for innovative applications, it is important to ensure the successful adoption of its technology across the eco-system and to define a multi-fold dissemination, exploitation, and communications strategy to provide relevant information to all stakeholders and facilitate market adoption of the project results. In this regard, Table 1 presents the strategy and a summary of proposed impact and dissemination targets and their status.

Table 1 - Summary of proposed targets and status

Category	**KPI**	**Targets**	**Status**
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	More effort towards 3GPP and IEEE/IETF and OPC/UA
	Number of contributions	30	16
Industry and scientific community	Keynotes and panels in major conferences	at least 6 keynotes and at least 2 panels	7 keynotes and talks 2 panel discussion (EuCNC, O-RAN)
	Number of publications (journals, conferences)	30	5 (accepted) Several more are under preparation
	Workshops in major conferences	at least 2	2 (organized)
	5GPPP/6GIA activities	Contribution to steering board, technology board, pre-standardization, architecture, vision, and societal challenges	6GIA webinar, SNS journal, SNS video, 5G-ACIA WI initiated, joined to the SNS Architecture WG
	Tutorials		Half-day tutorial at European Wireless'23

Influence towards academia	Training activities (summer schools)	2	Planned for project year 2 and 3
	Graduate, PhD courses	3	
Communication towards the general public	Website visits outside consortium	1000+	1003 (unique hits)
	Press release, research blog	10+	1 (published)
	Social media channel used	Twitter, LinkedIn, YouTube	Active

The DETERMINISTIC6G project website (https://deterministic6g.eu/) serves as a central hub for dissemination activities. The vision, objectives, work plan, consortium description, latest updates, and public deliverables are made available at the webpage. Moreover, to ensure the maximum possible exposure of the project, social media and networking tools (LinkedIn [https://www.linkedin.com/company/deterministic6g/] and Twitter [https://twitter.com/DETERMINISTIC6G]) are being used to provide updates on the project activities.

The following tables summarize the communication and dissemination activities conducted during the first year of the project. To increase the project visibility and to engage in insightful scientific discussions, dissemination of DETERMINISTIC6G activities at workshops and tutorials is targeted. A joint workshop under SNS projects DESIRE6G, PREDICT6G, and DETERMINISTIC6G was organized at EUCNC 2023. Similarly, a joint workshop under DETERMINISTIC6G and COST INTERATC was organized at PIMRC 2023. Table 2 presents the workshops, special sessions, and tutorial organized under the project for dissemination of the project goals and objectives to a wider audience. The tutorial session organized at European Wireless 2023 provided an overview of the latest developments in wired and wireless networks to support deterministic communication and its need for industrial applications. The tutorial slides are available on the DETERMINISTIC6G webpage. Such tutorials will also be organized further during the course of the project which will also form a basis for planned summer schools and will help disseminate the technical activities performed under DETERMINISTIC6G.

Table 2 - Workshops, special sessions and tutorials organized

Date	**Event**	**Title**
6-9 June, 2023	Workshop at EuCNC 2023, Gothenburg, Sweden	Joint workshop on "Future deterministic programmable networks for 6G" organized by PREDICT6G, DESIRE6G, and DETERMINISTIC6G https://www.eucnc.eu/programme/workshops/workshop-10/
5-8 September, 2023	Workshop at PIMRC 2023, Toronto, Canada	Joint workshop on "Vision and challenges on Sustainable and Intelligent Future IoT" organized by DETERMINISTIC6G and COST INTERACT https://pimrc2023.ieee-pimrc.org/program/workshops/vision-and-challenges-of-wireless-communication-for-future-industrial-iot/

6-9 June, 2023	Special Session at EuCNC 2023, Gothenburg, Sweden	Dependable wireless communication systems and deterministic 6G communication https://www.eucnc.eu/programme/special-sessions/special-session-3/
2-4 October, 2023	Tutorial at European Wireless 2023, Rome, Italy	An overview of time-bounded and deterministic communication https://ew2023.european-wireless.org/

In addition to the workshops and tutorials, keynote speeches, invited talks, project presentation, and participation in panel discussions were carried out for dissemination of project activities. Table 3 presents a list of these activities and their corresponding venues.

Table 3 - Project presentations and talks

Date	Event	Presenter and Title
6-8 February, 2023	ETSI research conference 2023, Sophia Antipolis, France	Dhruvin Patel, DETERMINISTIC6G poster presentation https://www.etsi.org/events/2130-etsi-research-conference#pane-6/
9–10 May, 2023	IEEE 6G Summit Dresden, Dresden, Germany	Joachim Sachs, “With 6G towards a Digitalized, Programmable and Intelligent World http://5gsummit.org/dresden/
11-12 May, 2023	Aachen Machine Tool Colloquium AWK’23, Aachen, Germany	Joachim Sachs, “Towards 6G - A Cyber-Physical Continuum for Industry 5.0” https://www.awk-aachen.com/?lang=en
22 June, 2023	O-RAN for Vertical Industry Workshop, Osaka, Japan	Joachim Sachs, “Connecting the cyber-physical world with 6G” https://www.o-ran.org/blog/o-ran-for-vertical-industry-workshop-osaka-june-2023
4-7 September, 2023	NetSys, Potsdam, Germany	Joachim Sachs, Keynote on "Creating a digitalized, programmable and intelligent world" https://www.kuvs.de/netsys/2023/program/
4-7 September, 2023	NetSys, Potsdam, Germany	James Gross, "Dependable Performance Guarantees for 6G Networks: Model-driven vs Data-driven?", in Future of Networking expert symposium https://www.kuvs.de/netsys/2023/program/zdn/
14-15 September, 2023	Fuseco Forum, Berlin, Germany	Hans-Peter Bernhard, “Deterministic Communication in 6G, Where We Are and Where To Go”, https://fokus-fraunhofer.lineupr.com/fuseco-forum-2023/

27-28 September, 2023	TSN/A Conference, Stuttgart, Germany	Joachim Sachs, "Towards Wireless End-to-end Deterministic Communication" https://events.weka-fachmedien.de/tsna-conference/home/

Another dissemination target of the project is to contribute technical outcomes to scientific venues in the form of publications. Table 4 presents the list of accepted publications and the corresponding venues. Further scientific publications are planned while some are already in the preparation phase based on the year end deliverables of the project.

Table 4 - List of accepted publications and venues

Venue	Authors and title
IEEE Access	Gourav Prateek Sharma, Dhruvin Patel, Joachim Sachs, Marilet De Andrde, Janos Farkas, Janos Harmatos, Balazs Varga, Hans-Peter Bernhard, Raheeb Muzaffar, Mahin K. Atiq, Frank Duerr, Dietmar Bruckner, Edgardo Montesdeoca, Drissa Houatra, Hongwei Zhang and James Gross, "Towards Deterministic Communications in 6G Networks: State of the Art, Open Challenges and the Way Forward", in IEEE Access, vol. 11, pp. 106898-106923, 2023
IEEE Globecom 2023	Samie Mostafavi, Neelabhro Roy, Gyorgy Dan, James Gross, "Causal Active Queue Management for Time Sensitive Wireless Links"
IEEE Globecom 2023	Samie Mostafavi, Rishi Nandan, Gourav Prateek Sharma, James Gross, "Latency Probability Prediction for Wireless Networks: Focusing on Tail Probabilities"
EuCNC special session 2023	Gourav Prateek Sharma and James Gross, "Challenges and Directions for Deterministic Communication in 6G"
EuCNC special session 2023	Mahin K. Atiq and Raheeb Muzaffar, "Time synchronization for deterministic communication"

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. The project partners continuously participate to standardization and regulatory bodies meetings such as 3GPP, IEEE and ETSI, industry alliances such as NGMN and 5G-ACIA. There are partners in the project consortium that are key drivers and active members of deterministic communication relevant standardization bodies. Moreover, the project is an active member in the European Union project partnership within the framework of Smart Networks and Services Joint Undertaking. DETERMINISTIC6G therefore succeeded in making strong efforts in standardization and regulatory activities. During the first year 15 proposals were submitted to 3GPP (FS_DetNet WI and TRS_URLLC WI) as well as 1 contribution to IEEE (IEEE 802.1 TSN Task Group). In the next project period, contribution efforts will be made towards IEEE, IETF and OPC-UA.

7.3 Next steps

During the first year of the project, considerable communication and dissemination activities have been carried out. In a similar fashion, several activities are planned, including scientific publications, standardization activities, and organization of workshops and special sessions. Moreover, summer schools and info days will be organized to have in-depth discussions of the project and to disseminate the knowledge to young PhD students and researchers. Lastly, participation at industrial conferences such as the OPC UA days and IEEE Industrial forum is planned. The project website and social media platforms will be used for announcements and dissemination of activities.

8 Conclusion and outlook

In this intermediate project report the main achievement made by DETERMINISTIC6G during the first year of the project are highlighted by covering the provided deliverables of the project and the ongoing activities in the different WPs.

The DETERMINISTIC6G project started with the identification of visionary use cases that require dependable time-critical communication provided by 6G systems. During this work, the detailed use case analysis and description was performed, including the derivation of KPIs and KVIs. In addition to the use case description, the guiding principles towards dependable time-critical communication were discussed, as well as the key architectural aspects of 6G deterministic communication were identified and described.

Considering the domain (communication, computation) specific requirements derived from the use cases and the specified architecture framework, the detailed, concept-oriented activities are initiated by focusing on 6G centric enablers, wireless-friendly design of E2E deterministic communication, deterministic support in the compute domain, security aspect and digital twinning of 6G network.

Regarding 6G centric enablers, the project produced results in the following major areas, 1) Packet Delay Correction to control the jitter to tens of milliseconds over the radio transmission ensuring predictable delay, 2) deep neural network-based latency prediction approach and related architecture framework, and 3) RAN resource allocation strategies for XR use case. In the next phase of the project, the evaluation of the above methods will be performed, and advanced, AI/ML-based latency prediction methods are planned to be developed.

Towards the wireless friendly design, the model of 6G DetCom node and alternatives for handling its stochastic characteristics are described. Moreover, a wireless-friendly, adaptive end-to-end scheduling framework covering the wired (TSN/DetNet) and wireless (6G) is proposed. To extend dependable services by covering the compute domain, the first architectural results to support time-critical services through Edge computing are also presented. Furthermore, a concept for seamless user plane integration of traffic handling in the compute and communication domains to ensure the proper handling of 802.1Qbv scheduled traffic is also described. In this track, in the rest of the project the focus will be on the control plane aspects.

During the first year of the project a security monitoring framework and a monitoring software have developed, by providing advanced monitoring solutions and detailed analysis of security threats within 6G networks. The Digital Twin related activities focused on the selection of parameters that are required to efficiently predict the future behavior of the 6G system and it continues with the development of various prediction strategies.

The first version of the simulation framework is released in the first year of the project. Its capability is to perform E2E simulations by leveraging different PDV models for wired bridges, wireless 5G nodes and processing delay models for the edge computing domain. Using different deployment scenarios and configurations, the first evaluation results describing the effect of PDV are available. In the upcoming months, the intention is to extend the framework towards supporting control plane features by providing a complete platform to validate the concepts developed in the project.

Regarding the dissemination, it can be concluded that the project has already succeeded in the promotion and sharing of the knowledge regarding dependable time-critical communication towards the international research community though publications, talks, workshops, panel discussions and tutorials. Furthermore, the project partners are active in the different standardization bodies, mainly in 3GPP and IEEE. In the upcoming months strong focus will be put to the preparation of publications based on the deliverables conveyed at the end of 2023.

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List of abbreviations

AI	Artificial Intelligence
CNC	Centralized network controller
COTS	Commercial Off-the-shelf
CPS	Cyber Physical System
DT	Digital Twin
E2E	End-to-end
GPD	Generalized Pareto Distribution
HARQ	Hybrid Automatic Repeat Request
ICT	Information and Communication Technology
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
MDN	Mixture Density Network
MEC	Multi-Access Edge computing
ML	Machine Learning
NEF	Network Exposure Function
NIC	Network Interface Card
NWDAF	Network data analytics function
OAI	Open Air Interface
OE	Occupational Exoskeleton
O-RAN	Open Radio Access Network
PDC	Packet Delay Correction
PDV	Packet Delay Variation
PTP	Precision Time Protocol
RAN	Radio Access Network
RAP	Resource Allocation Protocol
RSRQ	Reference Signal Received Quality
SDR	Software-defined Radio
TBS	Transport Block Size
TSCTSF	Time Sensitive Communication and Time Synchronization Function
TSN	Time Sensitive Networking
UE	User Equipment
XR	Extended Reality
ZSM	Zero-touch Service Management