[D2.1]

Release 1 of PREDICT-6G MDP innovations.

PREDICT-6G

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Abstract

This document is the first delivery of the Work Package 2 and contains the current status of the work on the multi-domain data plane (MDP). In this document, we define how we understand the determinism in the data plane and how we plan to enhance the determinism in different domains. In this document we include the first achievements of the PREDICT-6G project and the short- and long-term plans for the WP2.

Keywords

multi-domain data plane, MDP, TSN, 3GPP,

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Nature of the deliverable	R	
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PU	Public, fully open. e.g., website	✓
CL	Classified information as referred to in Commission Decision 2001/844/EC	
SEN	Confidential to PREDICT-6G project and Commission Services	

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Acronyms and definitions

3GPP	3rd Generation Partnership Project
AI	Artificial Intelligence
AICP	AI-driven Multi-stakeholder Inter-domain Control-Plane
AP	Access Point
AR/VR	Augmented Reality/Virtual Reality
DoA	Description of Action
DoS	Denial of Service
DT	Digital Twin
E2E	End-to-end
eBPF	extended Berkeley Packet Filtering
gNB	gNode B, radio base station in 5G NR
GRE	Generic Routing Encapsulation
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
KPI	Key Performance Indicator
MDP	Multi-domain Data-Plane
ML	Machine Learning
mMTC	massive Machine Type Communication
NIC	Network Interface Card
NR	(5G) New Radio

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OFDM	Orthogonal Frequency-Division Multiplexing
PCR	Path Control and Reservation
PDU	Packet Data Unit
PLC	Programmable Logical Controller
PREOF	Packet Replication, Elimination, and Ordering Functionality
TDD	Time Division Duplex
TSC	Time Sensitive Communications
TSN	Time Sensitive Networking
TWT	Target Wake Time
UE	User Equipment
URLLC	Ultra-Reliable Low Latency Communications
WP	Work Package
XDP	eXpress Data Path
XR	Extended Reality

Table of partners

Short Name	Partner
UC3M	Universidad Carlos III de Madrid
NOK	Nokia Solutions and Networks KFT
ERC	Ericsson Espana SA
INT	Intel Deutschland GMBH
TID	Telefonica Investigacion y Desarrollo SA
ATOS	ATOS IT Solutions and Services Iberia SL
GES	Gestamp Servicios SA
NXW	Nextworks
COG	Cognitive Innovations Private Company
SIM	Software Imagination & Vision SRL
AUSTRALO	AUSTRALO Alpha Lab MTU
POLITO	Politecnico di Torino
UPC	Universitat Politecnica de Catalunya

CNR	Consiglio Nazionale delle Ricerche
UNIPD	Universita degli Studi di Padova
IDE	InterDigital Europe Ltd

1 Executive summary

The PREDICT-6G project focuses on providing deterministic networking communication using existing wired and wireless technologies. In PREDICT-6G project we define determinism as the union of reliability, time sensitiveness and predictability, and is built around two novel concepts: a Multi-domain Data Plane (MDP) with deterministic enhancements and an AI-driven Control Plane (AICP). PREDICT-6G Work Package 2 (WP2) focuses on the research and innovation in the data plane in order to enhance its determinism in different domains. It is important to highlight that the focus of WP2 work is on **Layer 2** (L2) of the various data plane domains involved, enhancing predictability, and defining Key Performance Indicators (KPI), rather than on improving them.

One of the key aspects of D2.1 is how to handle the determinism in a scenario that involves more than one domain. For that, an extension of the current Time-Sensitive Communication (TSC) mechanism that allows to create **cross-domain flow splitting and joining** is proposed**.** Also, special focus is set on the **domain-border gateways** as enablers of the cross-domain determinism.

Another important aspect of D2.1 is proposing new mechanisms to **enhance L2 enhance L2 functionalities**, by introducing **key innovations** that will be proposed by PREDICT-6G, as an **AI-based dynamic scheduling** for massive Machine Type Communication (mMTC) traffic as the initial result of the *Dynamic Scheduling* activity. Also, we present an extensive experimental result of the **Time Sensitive Networking (TSN) support in Wi-Fi**, work which PREDICT-6G partners very recently published in peer-reviewed papers. Finally, another key innovation is the development of a **SW TSN switch** that is key for testing TSN capabilities on top of non-TSN networks (e.g., Rel-15 3GPP networks).

This document introduces how to support domain integration by using DetNet and RAW, setting up the basis for starting the integration of several different domains. We want to also mention the **contributions to the IETF** drafts of DetNet and RAW, as detailed in the deliverable.

Finally, we also describe how we are going to use Open APIs to integrate the Multi-Domain Data Plane with the PREDICT-6G control plane. We present, in this regard, an innovation for using **Digital Twin** (DT) in the 3GPP domain for simplifying the integration with control plane.

All the activities of the partners are summarized in a roadmap, which defines our current plans and, for the short-term, the content of the next WP2 deliverable.

2 Introduction

One of the pillars of PREDICT-6G is the Deterministic Data Plane, which provides the determinism as a combination of three key concepts: Time sensitiveness, Reliability and Predictability. As detailed in this document, the state of the art of data plane solutions and the inclusion of deterministic capabilities varies depending on the technological domains, making it evident that, as of today, there is not a single solution for supporting determinism in multiple technologies or domains. For that reason, PREDICT-6G aims to provide multi-technology multi-domain E2E (E2E) deterministic communications through a deterministic data plane solution. The PREDICT-6G WP2 focuses on research and innovation actions aiming at improving the determinism in the data plane.

The overall PREDICT-6G system architecture is depicted in Figure 1, as detailed in section 8 of PREDICT-6G Deliverable 1.1 ([1]), and is composed of two planes:

1. **Multi-Domain Data Plane (MDP):** providing integration, abstraction, and programmable exposure of multiple User-plane mechanisms (with different levels of intrinsic deterministic capabilities). As detailed in Figure 1, PREDICT-6G focus on wireless domains (3GPP, Wi-Fi) and on domains supporting DetNet.
2. **AI-driven Multi-stakeholder Inter-domain Control-Plane (AICP):** AI/DT based C/M-plane mechanisms with autonomous orchestration and assurance of E2E deterministic services.

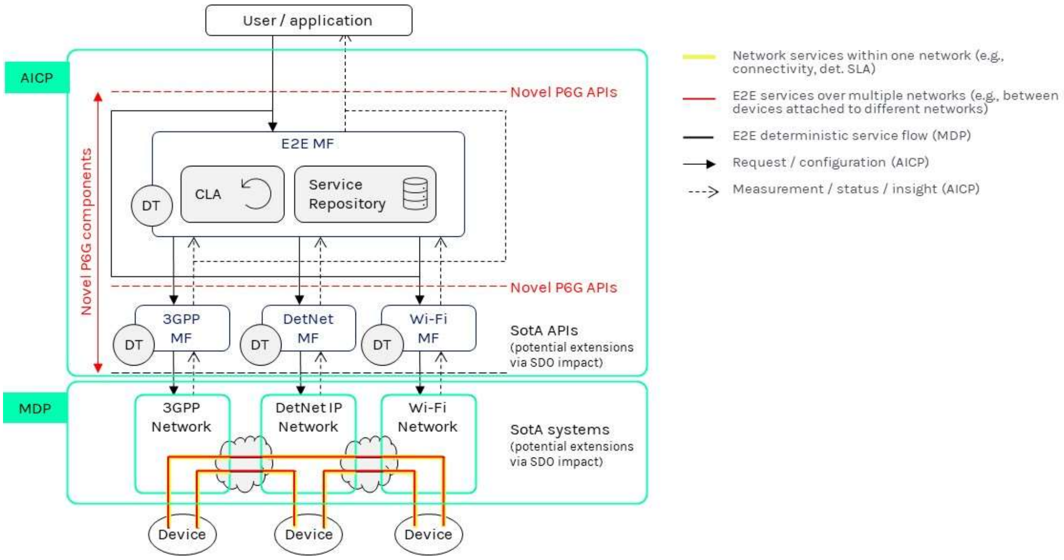

Figure 1 The overall PREDICT-6G system architecture.

This deliverable focuses on describing the multi-Domain data plane innovations performed during the first half-year of the project, and on reporting the plans for the rest of the 2023. The status of the multi-domain data plane architecture is presented in detail in Section 3.

2.1 Contributions to project KPIs

In the following subsection we highlight the contributions of WP 2 that have been achieved from the start of the WP2 activities (April-2023) to the date of the delivery of this document.

In the area of research and dissemination, WP2-related activities produced the following papers:

1. S. Sudhakaran *et al.*, "Zero-Delay Roaming for Mobile Robots Enabled by Wireless TSN Redundancy," *2023 IEEE 19th International Conference on Factory Communication Systems (WFCS)*, Pavia, Italy, 2023, pp. 1-8, doi: 10.1109/WFCS57264.2023.10144124.
2. [PUBLISHED] Alberto Morato et al., "Evaluating the Integration of Wireless Time-Sensitive Networking with Software-Defined Networking for Dynamic Network Configuration".
3. M. Llobet, M. Cabrera-Bean, J. Vidal and A. Agustin, "Optimizing Access Demand for mMTC Traffic Using Neural Networks," in IEEE Transactions on Vehicular Technology, doi: 10.1109/TVT.2023.3294724.
4. M. M. Roselló, J. V. Cancela, I. Quintana and M. Lorenzo, "Network Digital Twin for Non-Public Networks," 2023 IEEE 24th International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM), Boston, MA, USA, 2023, pp. 495-500, doi: 10.1109/WoWMoM57956.2023.00086.

In the area of contribution to Standard Developing Organizations (SDOs), we contributed to the IETF drafts of DetNet and RAW. More concisely, we contributed 4 adopted Work Group (WG) drafts [2][3][4][5] and 2 individual contributions [6] [7]. Please refer to section 4.4 for more details.

Regarding E2E demonstrations, we accomplished to set up at 5Tonic a single-domain simulation of Smart Factories use case [1], as is described in section 4.2.

2.2 Deliverable contents

This document is structured as follows:

Section 3 details the architecture of our Multi-Domain Data Plane and shows the proposed solutions to guarantee the determinism across the domains.

Section 4 describes the research and innovation activities that the partners involved in task 2.1 performed at L2 in different technology domains. We present the internal organization of the different activities, which have the objective of boosting the collaboration between different research teams, and also organize the activities depending on their main focus in three categories: (i) Fundamental research with focus on the L2 of wireless technology, (ii) Standalone demonstrations, which aim to provide a Proof of Concept (PoC) of different enhancements with soft integration with PREDICT-6G Control Plane, and (iii) Integrated demonstrations, which aims to provide E2E PoCs of the whole project, with tight integration with the control plane.

Section 5 defines the way of interconnecting different technology domains by using DetNet and RAW.

Section 6 defines the way in which MDP will expose deterministic capabilities towards the PREDICT-6G Control Plane, by using APIs defined with OpenAPI language, and elaborates how to support those APIs in different technology domains.

Section 7 presents the roadmap of the innovations in the time of delivering this document.

Finally, Section 8 describes the foundations of the PREDICT-6G project regarding the determinism in the data plane.

3 Data plane Architecture and Determinism

This section describes the architecture of PREDICT-6G Multi-domain (multi-technology) Data Plane (MDP).

3.1 Overview

The deployment of E2E services in the PREDICT-6G MDP (Figure 2) is composed of two levels:

- The **services within a domain's** boundary span between per domain service endpoints that are within the same domain.
- The **PREDICT-6G E2E services** are defined between E2E service endpoints that may be in different domains.

The E2E service is composed by chaining domain specific services, with inter-domain integration between domains and at domain boundaries.

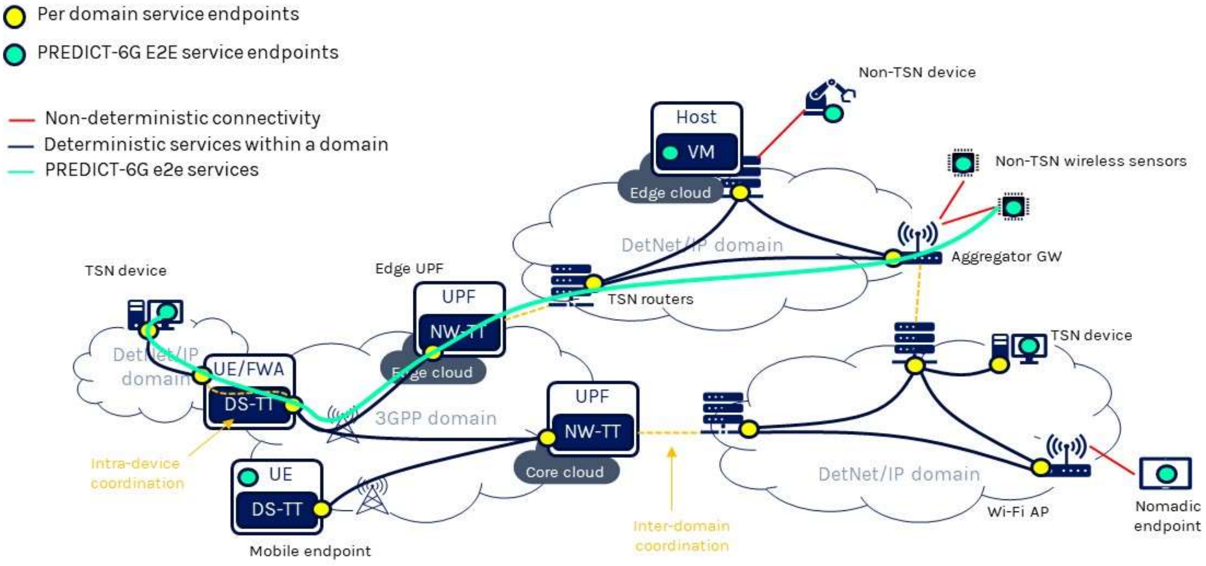

Figure 2 Services and endpoints within the MDP

The PREDICT-6G MDP consists of three fundamental components (provided by physical or virtual devices) that implement capabilities required to provide the above services:

- At the edge of the network there are the PREDICT-6G E2E service endpoints, i.e., the TSN or Non-TSN capable devices that are the endpoints of the deterministic service flows. These devices are either the deterministic data producers or consumers within an E2E service flow.
- In general, the E2E deterministic service flows are realized by more than one networking technology domain with domain specific deterministic data delivery services. The devices of these domains ensure deterministic data delivery within their domain with mechanisms such as packet replication, elimination, and ordering functionality (PREOF), hold-and-forward, etc.

- At the edges of each technology domain there are the domain specific service endpoints. On the one hand, these terminate the domain specific service flows within their domain. On the other hand, they participate in the cross-domain interworking as they attach their domain to other domains, accept and inject traffic from and to other domains, support harmonized E2E path selection, data plane configuration and multi-domain splitting of deterministic mechanisms.

To achieve E2EE2E determinism, the following high-level enablers need to be present in the MDP components:

- Deterministic data generation at the device (including application, kernel, NIC, virtualization layers, etc., for the entire data path from program code to TX on wire/waveform).
- Deterministic schedulers at each hop (with proper per-hop behavior configured to support the E2E service parameters): providing deterministic and predictable transmission opportunity, bandwidth, buffering delay, propagation delay, and zero congestion loss.
- Cross-domain interworking for harmonized E2E path selection, data plane configuration and multi-domain splitting of deterministic mechanisms. Providing E2EE2E deterministic services for a set of E2EE2E flows (e.g., IP flows) across multiple technology domains requires that each domain is configured to recognize the same set of packets as being part of the same deterministic service. Each domain then needs to treat the packets classified in the service according to the deterministic requirements that were delegated to the domain during E2EE2E service composition.

3.2 Deterministic schedulers and PREOF

Individual domains, providing domain specific deterministic services, implement mechanisms for deterministic packet scheduling for bounded low latency packet delivery:

- Per-flow filtering, buffering, policing, and shaping, credit-based shaper (IEEE 802.1Qav [8]): the basic mechanisms to ensure deterministic packet deliver is based on specially designed packet handling algorithms (filtering, buffering, etc.) controlled by flow level traffic prioritization. The IEEE 802.1Qci[9] Per-Stream Filtering and Policing (PSFP) standard enhances network resilience by selectively filtering and controlling individual traffic streams. This feature helps prevent situations where bridges and receiving endpoints become overwhelmed by excessive traffic, whether caused by malfunctions or intentional Denial of Service (DoS) attacks. By employing rule matching, the stream filter allows frames with specific stream IDs and priority levels while applying designated policy actions to others. The coordination of all streams occurs at their respective gates, following a similar approach to the 802.1Qch [10] signaling. Additionally, predefined bandwidth profiles are applied to each stream through flow metering.
- Pre-emption of lower priority packet transmission by higher priority. This means that an ongoing transmission of a packet of a lower priority flow can be interrupted in case a higher priority flow presents a packet to be transmitted. After transmitting the packet of the higher priority flow, the interrupted transmission is resumed.
- Delay compensation (hold and forward) is needed for links with variable propagation characteristics (e.g., wireless). These links introduce unwanted amount of jitter in packet delivery. Hold and forward mechanisms can de-jitter the affected flows by transmitting early packets at fixed intervals instead of transmitting them on a best effort basis, i.e., as soon as possible.

Besides deterministic packet delivery, TSC technologies must provide their services at the highest possible reliability: they must ensure virtually zero packet loss. The following enablers are commonly applied to achieve this requirement:

- PREOF: packet replication, elimination, and ordering function, using disjoint transmission paths (e.g., 802.1CB [11]). PREOF is used to avoid packet loss due to equipment failure. It is a per-packet 1+n redundancy approach, without failure detection or switchover mechanism in place. At replication, multiple copies of the same packet are created and sent over as many maximally disjoint paths, then combined. At elimination, only the first successfully transmitted copy of each packet is kept and transmitted further in the correct order (Figure 3).

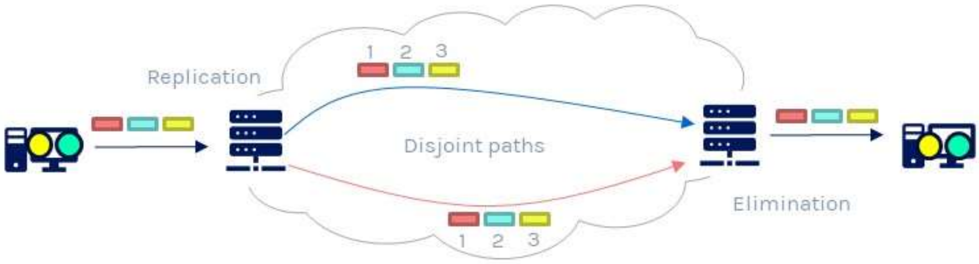

Figure 3 PREOF: packet replication, elimination, and ordering

- Path Control and Reservation (PCR), with admission control (802.1Qca [12], RFC 7813 [13]): PCR use the Intermediate System to Intermediate System (IS-IS) in TSN networks to enable explicit path control, as specified in clause 45 of [12]. This goes beyond the limitations of Shortest Path Bridging (SPB) by providing enhanced capabilities for establishing and managing explicit forwarding trees within a TSN network domain.

3.3 Cross-domain determinism

State-of-the-art TSC mechanisms such as PREOF, hold-and-forward, etc., are defined per technology domain. In PREDICT-6G these should be distributed and synchronized across multiple domains (distributed TSC). For example, E2E PREOF requires that replication and elimination functionality are mapped toto different domains of different technologies, therefore domain specific technologies needed to be capable of activating only part of their PREOF functionality and apply them to the same set of packets (see cross-domain flow harmonization). De-jittering or enforcing on-time packet delivery through hold and forward mechanisms also requires coordination between domains.

To enable E2E deterministic services, the following requirements are addressed in PREDICT-6G concerning cross-domain determinism:

- Harmonization of intra-domain service configuration (e.g., scheduler parameters; bandwidth allocations; delay budgets; etc.)
- Cross-domain path selection and with path capabilities matching with E2E service requirements.
- Cross-domain PREOF inter-working (source domain performs packet replication, destination domain performs packet elimination – if the domains are implemented with different technology)

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3.3.1 Potential enablers of cross-domain determinism

Cross-domain flow splitting and joining (Figure 4) with per packet/flow replication/elimination context transferred between domains: each individual TSC technology supports these mechanisms within its own domain. To enable such features in the PREDICT-6G multi-technology, multi-domain environment, these deterministic packet delivery enablers must be coordinated along the E2E path.

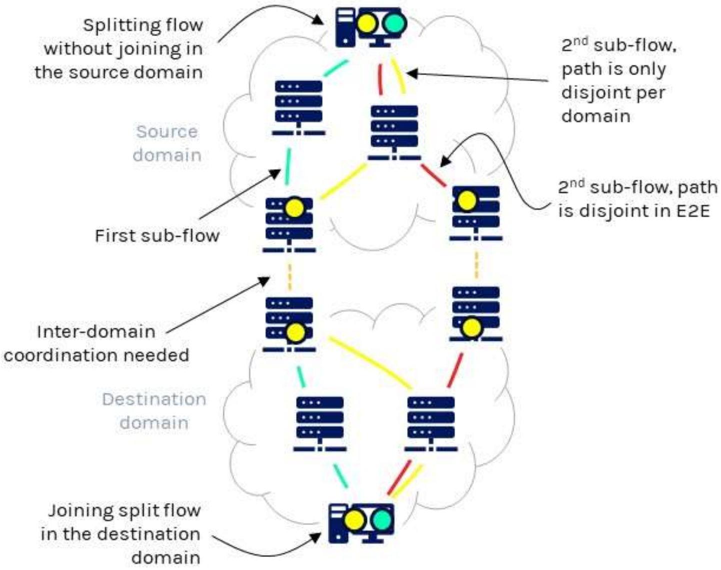

Figure 4 Cross-domain flow splitting and joining

Domain-border GateWays (GWs) (Figure 5 and Figure 6) having NICs in both domains: n-stack devices, that can be attached to at least two domains of different technology. Such devices implement the networking stacks of the technology domains that they are interconnecting and a relay functionality that handles packet routing between these stacks. Note that the physical GW can consist of multiple virtual GWs connected with an internal virtual network. The internal packet forwarding mechanisms of such GWs should also support deterministic packet delivery services.

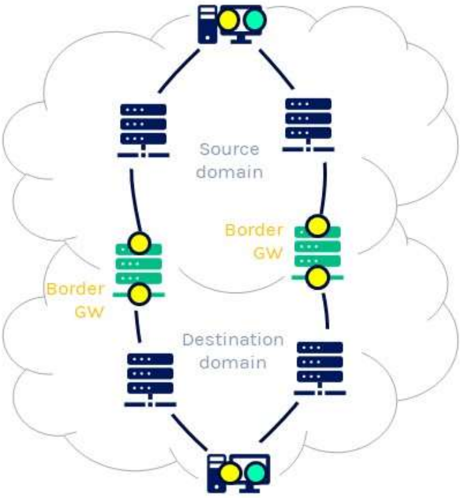

Figure 5 Domain border GWs to enable cross-domain determinism.

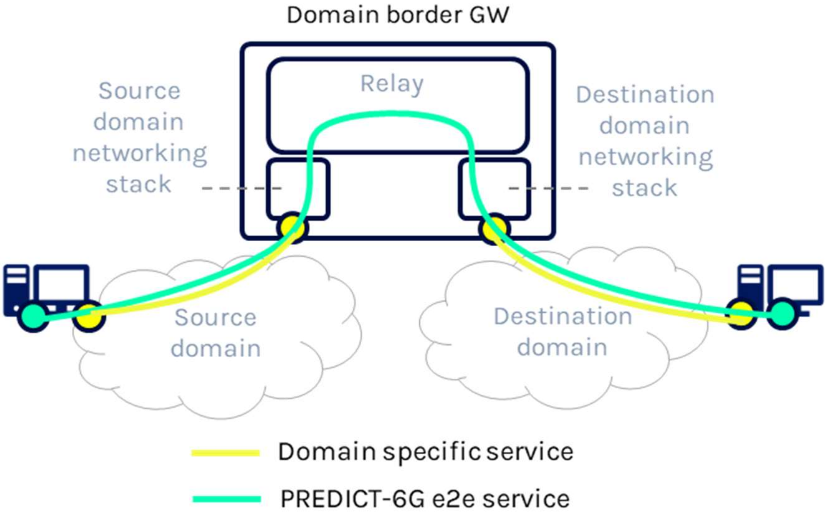

Figure 6 Domain border GW internal structure

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4 Enhancements at Layer 2

One of the tracks we follow in WP 2 is the research of enhancement at L2 level. The main goal of this track is to provide per-domain mechanisms that improve the determinism in any of the pillars defined in PREDICT-6G, i.e., reliability, time-sensitiveness, and predictability. For that, we define several activities coordinated by Task 2.1 that aim to research, develop, and implement enhancements in the domains at L2. The organization of these activities is described in the next sections.

4.1 Background

Currently there are different initiatives that provide determinism in different domains. For Ethernet (fixed) networks, IEEE provides a set of standards related to TSN defined by IEEE 802 [14]. This work is a continuation of the former IEEE 802.1 Audio Video Bridging (AVG) Task Group and focuses on enhancements in Ethernet Networks for time-sensitive applications. Some relevant standards are: (i) Timing and Synchronization for Time-Sensitive Applications (IEEE 802.1AS-2020 [15]), which describes the mechanisms for improving the time synchronization in TSN; (ii) Frame Replication and Elimination for Reliability (FRER)[11], which defines the mechanism for enhancing the reliability; (iii) Enhancements for Scheduled Traffic [16], with enhancements in time-based schedulers and, (iv) Forwarding and Queueing Enhancements for Time-Sensitive Streams, which specifies the Credit Based Shaper [8] and Path Control and Reservation [12].

Based on the previous standards, 3GPP defines the support of TSN in the TS 23.501 Rel.16 [17], where new TSN Translators are defined in the data plane. The Device-Side TSN Translator and the Network-Side TSN Translator offer TSN ports in the edge of the 5G System and implement the TSN features (Time Synchronization, Hold-and-Forward, etc.) defined in TS 23.501 [17].

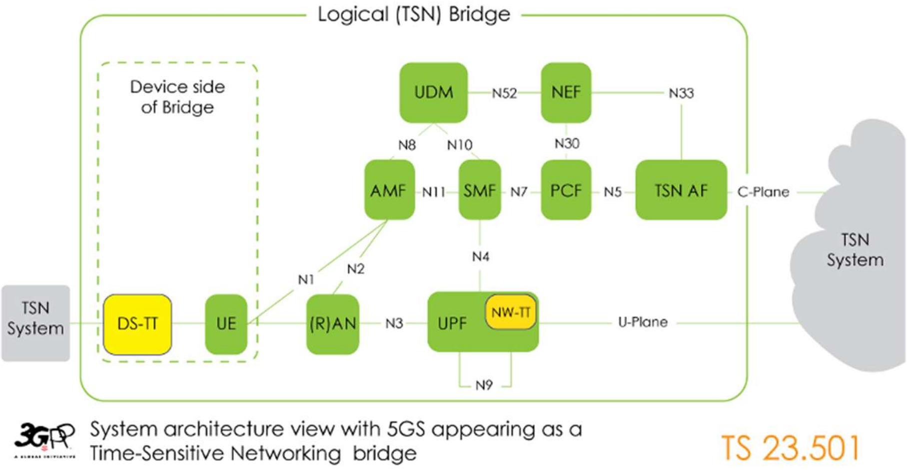

Figure 7 5GS as TSN bridge

For IP networks, the IETF Deterministic Networking WG focuses on deterministic data paths that operate over L2 bridged and L3 routed segments, where such paths can provide bounds on latency, loss, packet delay variation (jitter), and high reliability. The scope of the DetNet WG includes: (i) overall architecture,

(ii) data plane specification, (iii) data flow information model and, (iv) related YANG models. In the data plane, two standards are defined: (i) IP [18] and (ii) MPLS[19]. In Rel. 18, 3GPP incorporates the support of DetNet for IP based PDU Sessions, as described in the Figure 8.

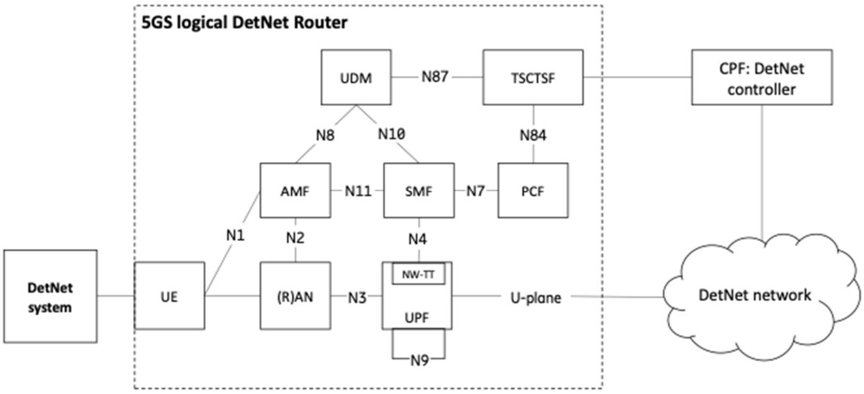

Figure 8 5GS Architecture to support IETF DetNet

For Wi-Fi networks, IEEE 802.11 standardization groups have worked to enhance not only throughput, but latency and reliability too, with the addition of new features such as OFDM numerology, improved wireless time synchronization, target wake time (TWT), and multi-link operation defined in 802.11ax and 802.11be (Wi-Fi 6 and 7). These features can enable the implementation of TSN features such as time synchronization, thanks to the HW supported time stamping in time synchronization messages; time-aware scheduling, thanks to improvements in the control of the medium access to avoid long contention times by mechanisms such as OFDMA and TWT; as well as TSN redundancy through a single radio interface through multi-link operation (MLO).

4.2 Cluster of Task 2.1 activities

One of the main outcomes of our project meetings is the organization of the contributions planned in Task 2.1. In the DOA of the project, we included several enhancements for L2 in different domains (radio scheduling, integration, 3GPP networks, Wi-Fi) that are classified according to their scope in the following categories:

1. *Fundamental research:* The activities included in this category are related to fundamental research. Due to the nature of this research, we do not expect to have a full implementation of the results to be used in any of the demonstrations, as in most of the cases the research group works using simulations. Although the activities can contribute to any of the objectives of PREDICT-6G, their focus is on the production of scientific articles.
2. *Standalone demonstrations:* This category involves those activities that aim to extend the fundamental research and demonstrate it in a standalone demonstration. Standalone means that the integration of the data plane with the PREDICT-6G control plain could not exist or be limited. As well as the other categories, the activities classified in this one can contribute to any objective, but they have a focus in the contributions to SDO.

3. *Integrated demonstrations:* This category includes the demonstrations that are defined in the DOA of the project. The activities of this category aim to create an E2E demonstration, including the integration with AICP. The main contribution of these activities is the delivery of PoCs defined in the project.

Figure 9 contains the current classification of the different activities included in Task 2.1, classified by colors highlighting their main category (blue: fundamental research, red: standalone demos and green: integrated demos):

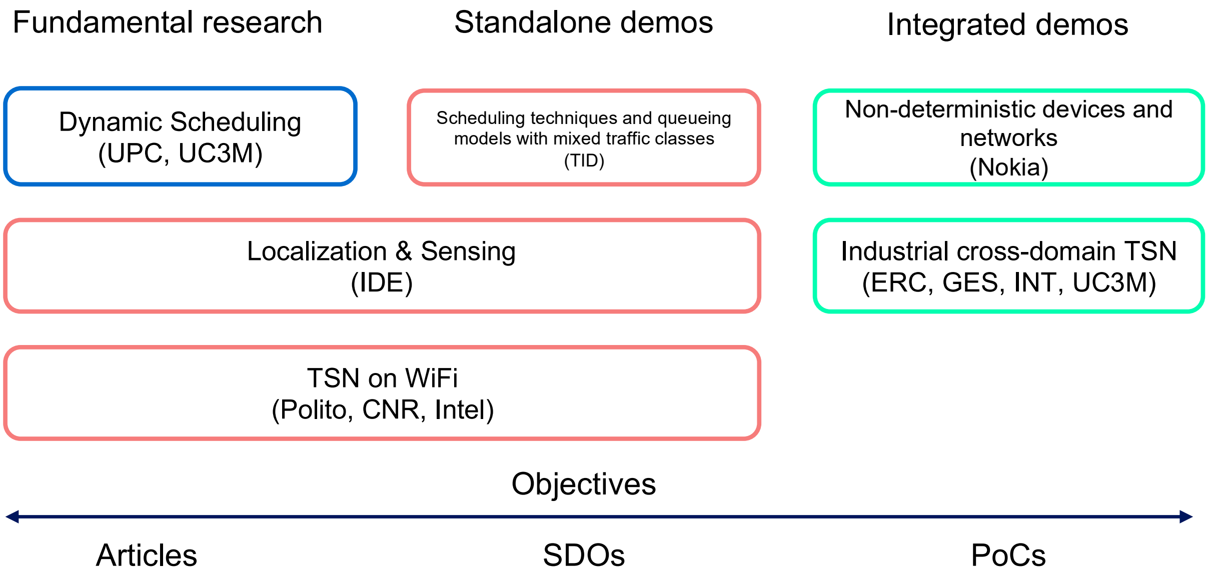

Figure 9 Cluster of T2.1 activities

In the following subsections, we review the status of each activity and the plans for the rest of the year, focusing on the definition of the work to be delivered in the next Deliverable 2.2.

4.3 Dynamic Scheduling

Dynamic Scheduling aims to perform fundamental research in dynamic scheduling of radio resources, which is appliable for both 3GPP and Wi-Fi wireless domains.

4.3.1 Work Description

In the boundaries between L1 and L2, dynamic scheduling algorithms will be designed to assign radio resources to different requesting flows in both uplink (UL) and downlink (DL). In a first stage, agnostic scheduling techniques have been developed for allocating flows from different users on TDD frames. In a second stage, the proposed schedulers will be simulated and evaluated in the context of 5G URLLC networks, and the interface for the scheduler communication with the control plane will be defined.

In the wireless segment, multiple users establish connections with a gNB (or Access Point (AP)) to exchange diverse flows with the network, including time-sensitive and best-effort flows. Time-sensitive flows will convey isochronous, TSN periodic traffic from control devices (e.g., sensors and actuators) and aperiodic bursty traffic from other time-sensitive applications such as Augmented Reality / Virtual Reality (AR/VR). On the other hand, best-effort flows carry aperiodic traffic that has less stringent or sometimes no specific requirements regarding latency, jitter, and throughput.

The Radio Resource Management module (RRM) of the coordination node is responsible for managing radio resources (e.g., subcarriers and time slots) and packet scheduling for both UL and DL. As the number of radio resources is limited, proper scheduling algorithms and admission control mechanisms at the RRM are essential to ensure the best QoS to the tenant user terminals (UT) with the available radio resources and the specific channel conditions that may change over time.

During the first half of PREDICT-6G we have investigated how to schedule in a wireless network multiple concurrent flows of traffic with diverse QoS requirements. We have focused on offering constrained latency to time-sensitive flows based on the optimization framework presented in [20]. Initial research on multicarrier (OFDMA) scheduling in slowly time-varying industrial scenarios has been carried out obtaining some encouraging preliminary results. In parallel, we have started to study the use of **reinforcement learning (RL)** for optimizing dynamically the fraction of time assigned to uplink and downlink in every time division duplexing (TDD) super frame. Furthermore, in the first semester (M6), we have developed a new Neural Network (NN) based contention access mechanism to attend traffic that is distributed through a RACH (Random Access CHannel) in a contention-based mode [21].

For the rest of the year, we plan to consolidate, test, and assess the most promising scheduling solutions developed during the first semester. Results will be presented in D2.2 in project M11.

4.3.2 General Architecture

The general scheduler architecture proposed is shown in Figure 10 for an illustrative simplified case where each of the two gNBs (or APs) serve some users. The architecture consists of multiple gNBs (or APs) with overlapping coverage areas that are interconnected and can exchange information with sufficiently large rate and reduced latency to implement coordinated spatial-reuse and multi-cell scheduling (also called coordinated OFDMA in the Wi-Fi context [22]). We assume there are independent FIFO queues per flow and per link (UL & DL).

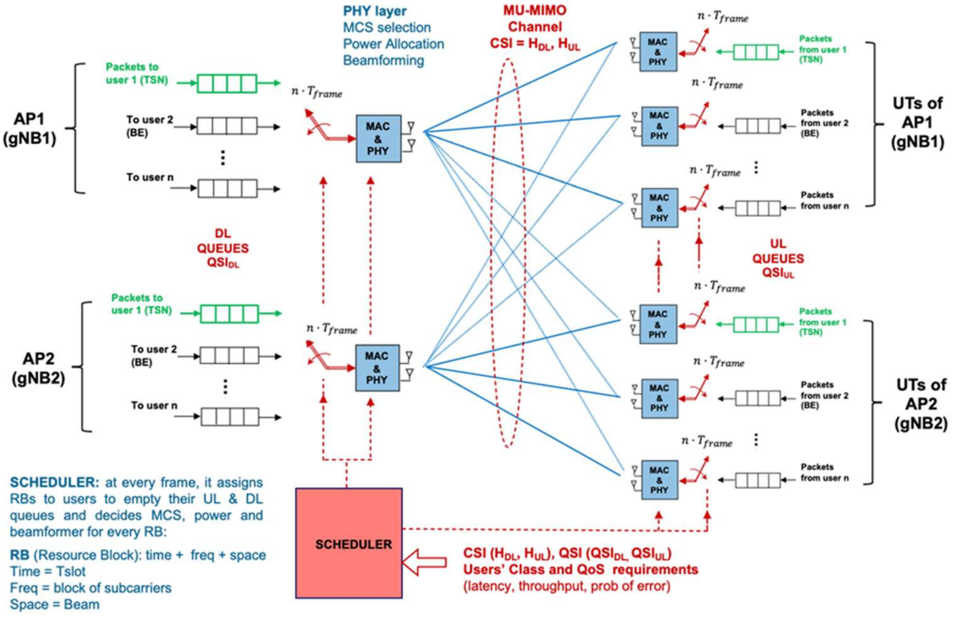

Figure 10 Architecture of the scheduler including two coordinated gNBs (or APs)

In the time division duplexing (TDD) communications context, UL and DL intervals are dynamically designed on a per-super frame basis. Inclusion of preambles, guard times and definition of the minimum indivisible unit to be allocated, i.e., the resource block (RB), is flexible enough to allow compatibility with both 3GPP and Wi-Fi in an OFDMA coordinated access mode, and is compatible with 802.1Qbv [16] for isochronous traffic. In the second year of the project, the proposed scheduling algorithms will be adapted and evaluated for 5G URLLC networks.

The decision on RBs allocation is taken by the scheduler at the beginning of each TDD frame (super frame). In a wireless channel, the transmission rate of available RBs is not constant, but it varies along time, frequency and spatially in a multi-antenna scenario. The number of bits that can be transmitted in a specific RB is directly determined by the MCS and transmitted power, which at the same time depend on the targeted reliability in terms of the Packet Error Rate (PER) and the signal to interference-plus-noise ratio (SINR).

4.3.3 Scheduling algorithms

A hierarchical/modular approach will be designed for the scheduling within the Wireless Node at the AP. This approach involves an upper-level scheduler that dynamically decides the allocation of slots for UL and DL transmissions. Once the decision regarding the allocation of resources to UL and DL is made, the next scheduling levels, i.e., the UL and DL schedulers, will operate independently. The DL scheduler will coordinate the allocation of RB for different types of DL traffic, including DL Isochronous TSN traffic, DL Asynchronous TSN traffic, and DL best-effort traffic. A parallel approach will be followed for the UL.

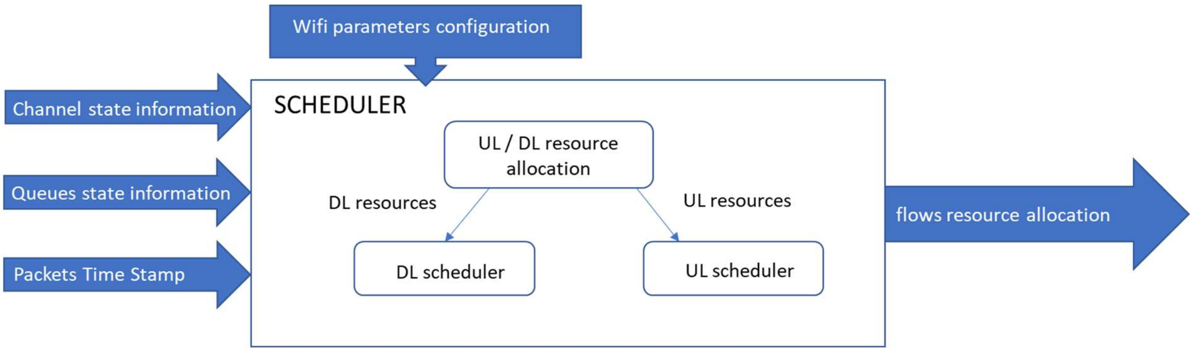

Figure 11 Scheduler Overview

The upper-level scheduler for the allocation of time to DL/UL slots will be designed **based on RL techniques** similarly to the ones applied in [23]. The UL and DL schedulers for the allocation of RBs to the different types of traffic in the UL and in the DL respectively will be designed by **solving an optimization problem with different constraints** following the methodology provided in [20].

4.3.4 Extensions

Extension to multi-antenna by applying **beamforming techniques** will be developed to improve reliability and spectral efficiency in the presence of multiple co-channel users. Affordable real-time solutions will be addressed.

On the other hand, **coordinating multiple gNBs (or APs)** will be analyzed to improve the spectral efficiency and reliability of wireless access, allowing the individual per gNB RRM modules to make better scheduling decisions.

As explained previously, we mostly consider joint TSN and BE traffic to be scheduled in a duplexing (TDD) super frame of the Dedicated Traffic Channel (DTCH). In addition, we must attend **traffic that is distributed through a RACH** (Random Access CHannel) in a contention-based mode without coordination between access points (gNBs). In [Llob,23] we have first derived the analytical expression of the optimal Access Class Barring (ACB) parameter as standardized by 3GPP. Secondly, we predict the type and number of accessing devices from measurements acquired by the Base Station (BS) by employing **Neural Networks (NNs)**. These estimates are then used to effectively implement the **optimal barring scheme in the RACH**. Performance results are very close to the theoretical bound with 3GPP standardized traffic models.

4.3.5 Expected outcomes.

The previous architecture, environment and scheduling algorithms will be implemented in a simulator to measure KPIs for certain types of traffic, and according to the recommendations issued in D1.1. Some of the scheduler features will be selected by considering their potential gain in terms of QoS (delay, jitter, throughput, etc.) as well as the feasibility of generating an affordable real-time solution.

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4.4 TSN on Wi-Fi

This activity involves the research and demonstration of the TSN mechanisms working with wireless networks, specifically with Wi-Fi.

4.4.1 Target Wake Time scheduling

Target Wake Time (TWT) scheduling is a promising approach that limits the active stations (STAs) to only those that are involved in a transmission session. The challenge lies in creating the sessions, establishing their duration and the STAs that belong to them, a.k.a. the TWT allocation problem. The deterministic nature of TSN flows adds further complexity to the problem.

TWT was initially introduced for S1G capable devices (initially IEEE 802.11ah-2016, now in IEEE 802.11-2020). It is an optional feature for Wi-Fi 6 stations (HE Capabilities, IEEE 802.11ax-2021) but already mandatory for APs, and it is expected to become mandatory for STAs in Wi-Fi 7 (latest 802.11be March 2023 draft is behind paywall). From IEEE 802.11-2020, "Target wake times (TWTs) allow STAs to manage activity in the BSS by scheduling STAs to operate at different times in order to minimize contention and to reduce the required amount of time that a STA utilizing a power management mode needs to be awake". By enabling devices to sleep for extended periods, TWT scheduling conserves energy and minimizes contention between active stations.

The objective of this research is to enhance Wi-Fi networks by achieving transmission delay determinism through the implementation of TWT scheduling. The scheduler can be implemented as a Machine Learning (ML) algorithm, based on RL.

By optimizing TWT scheduling, by learning the optimal wake times for connected stations, we aim to improve energy efficiency, maximize throughput, and enable deterministic packet delivery. The non-determinism of Wi-Fi networks come from the random backoff of CSMA/CA Distributed coordination function (DCF), which prevents to know in advance how long a station will have to wait before accessing the medium and transmitting a packet. This is particularly crucial whenever many stations are active in the same and neighboring BSSs. To address this issue, TWT can be used to wake one device at a time, so that the (only) awake device can access the channel in deterministic time without any backoff.

Additionally, using Multiuser (MU) capabilities may help achieve determinism. In OFDMA, Resource Units (RU) can be concurrently allocated to different users to allow for parallel transmission using frequency diversity. Similarly, with MU-MIMO and precoding, spatial diversity can be exploited to allow for low-interference parallel transmission in the same band.

4.4.1.1 Scheduling problem

We will address the following scheduling problem. Every time the AP has a transmission opportunity, it can ask STAs to submit their traffic requirements, akin to a Buffer Status Report Poll. Then, a scheduling algorithm can be executed at the AP, which can notify stations about the scheduling decisions, similarly to Triggers, but using TWT commands.

The stations, $S = \{s_1, s_2, \dots s_n\}$, require deterministic traffic flows $F = \{f_{11}, f_{12}, f_{21}, \dots f_{nm}\}$. Each flow f_{ab} is associated with a priority p_{ab}, and latency and throughput requirements l_{ab} and t_{ab}, respectively. More formally, we can write:

$$\begin{aligned} \max \quad & \sum_{fab}^{F} p_{ab}\, x_{ab} \\ s.t. \quad & l_{ab}x_{ab} \le L_{ab} \\ & T_{ab\ ab} \ge t_{ab}x_{ab} \end{aligned}$$

where L_{ab} and T_{ab} are the target latency and throughput for the admitted task, and x_{ab} is a binary variable that takes 1 if flow ab is selected for transmission and 0 otherwise.

4.4.1.2 Objective of the optimization policy

Multiple factors can be considered to decide the optimal scheduling policy:

- Delay and/or throughput requirements mandated by the traffic flows/stations, as more delay-tolerant flows could be scheduled with lower priority.
- Traffic load, which would determine the radio resources needed to avoid congestion.
- Type of traffic, as persistent scheduling could be used in case of constant traffic load, as opposed to intermittent traffic.

Given the problem input, the objective of the optimization policy can be selected as to output:

- The set of (stations, flow) pairs that can be scheduled deterministically while respecting the constraints that they require.
- Admitting all STAs, the deterministic delays that can be guaranteed to all stations/flows chosen according to their priorities.
- Energy and throughput requirements could be considered as well.

Other challenges can be addressed as well, specifically:

- Supporting determinism when also legacy stations, e.g., IEEE 802.11b/g, are part of the BSS. Legacy STAs that do not support TWT may void TWT benefits also for TWT compatible STAs.
- Mitigating external interferences, as neighboring BSS will not respond to TWT commands, therefore they may try to contend the channel during wake times of TWT STAs.
  Exploring the potential applications in time-sensitive industrial networks, assuming that no neighboring BSS is present.

4.4.1.3 Exploiting TWT to recreate 802.1 Qbv

As previously explained, TWT is capable of scheduling wake periods for the STAs to transmit, also seen as opening and closing gates from STAs. From this point, it is straightforward to see that TWT matches perfectly with 802.1Qbv, as is stated in [24].

However, further works needs to be done in this direction: Is this enough to achieve good TSN metrics (small delay, low jitter, ...)? Does it overpass other solutions? What are its deterministic bounds? We plan to tackle all these questions to find out the potential of this solution.

Focusing first on the last question, using Network Calculus we model the service curve of each user queue relaying on the periodicity, the opening time and the transmission rate. The fact that two queues are opened at the same time influences in their performance, and this must be modelled having into account the priority of both queues. Notice that 802.1Qbv does not implement pre-emption by its own, hence, packets from higher priority need to wait if a packet of lower priority is currently being transmitted.

However, the main issue comes from the fact that the wireless medium is not 100% reliable. Hence, the service curves need to capture this characteristic, both the failure of a transmission and the retransmission of the faulty packet with a higher priority.

4.4.2 Assessment of TSN over Wi-Fi (IEEE 802.1 Qbv [16])

Determinism over Wi-Fi can be achieved through the introduction of the IEEE 802.1 TSN on top of the MAC services.

TSN defines a family of standards, originally conceived to improve the timeliness of wired networks (e.g., Ethernet). However, recently, several research activities have been undertaken to assess the adoption of TSN by wireless systems such as Wi-Fi and 5G [25].

Among the various opportunities offered by TSN, two standards appear particularly appealing to enhance determinism, namely IEEE 802.1AS (synchronization) and IEEE 802.1Qbv (traffic shaping and scheduling). The goal of this research is to investigate how the standards can be implemented on Wi-Fi networks. The activities that will be carried out concern mostly tests on experimental setups and simulations.

Practical tests aim at assessing the actual feasibility of the objectives. However, due to practical constraints they will refer to scenarios with a limited number of devices. Conversely, simulations will refer to wider networks in terms of both number of devices and geographical extension. Notably, practical tests will also allow to characterize the behavior of the components used, particularly in terms of the delays they introduce. This represents a key aspect, since the achievement of E2E deterministic services in PREDICT-6G requires that even the components' delays are carefully evaluated.

The full characterization of the components will also give the possibility of carrying out much more realistic simulations. Indeed, very accurate models of the components (Stations, Switches, Access Points, etc.) can be implemented and used in the simulation sessions.

A very first set of experiments has been already carried out to assess the possibility of achieving TSN synchronization over a Wi-Fi network. In this respect, a prototype TSN wireless network was implemented in which two Intel NUCs, equipped with i5-1135G7 processors, were connected through their wireless interfaces that run a TSN driver implementing both the IEEE 802.1AS and Qbv standards. The synchronization on the network was achieved through Wi-Fi, with one NUC acting as Grand Master and the other as Follower. Figure 12 shows the measured synchronization offset.

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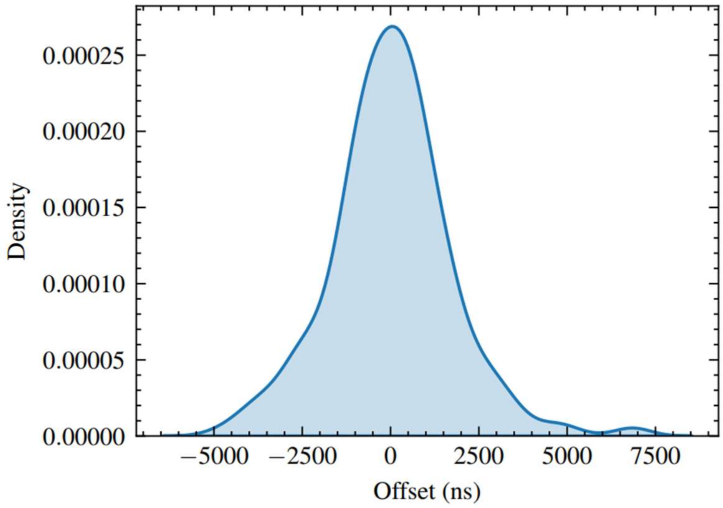

Figure 12 Synchronization offset between the two NUCs

The obtained results are: mean value = 21.7 ns, max = 4873 ns and min = -4934 ns.

Moving from these achievements, further activities can be envisaged as:

- Evaluation of the synchronization offset for a network with more STAs.
- Evaluation of latency.
- Assessment of IEEE 802.1 Qbv for traffic scheduling.

Particularly, with the achieved synchronization, the latency can be obtained as the difference between the times of packet arrival and sending, measured on the (synchronized) devices. Also, using adequate timestamps, it will be possible to determine the times necessary to execute the various steps involved in the E2E communication, which includes the protocol stacks execution times, queuing latencies, actual data transmission, etc., in such a way to achieve a complete device characterization.

Furthermore, the availability of IEEE 802.1 Qbv allows to implement time-aware packet scheduling and prioritization, facilitating the coexistence of real-time and best-effort traffic. Notably, this opportunity can be exploited in conjunction with the scheduling techniques based on the Target Wake Time discussed above.

4.4.3 Dynamic re-configuration of TSN-based wired/wireless networks.

In the context of PREDICT-6G, there is the need of re-configuring the data planes of networks because of analyses and/or predictions that detect or envisage anomalies, with the goal of ensuring and maintaining E2E bounded latency and reliability. This requires the seamless switching of communication flows among different links, that may be either wired or wireless. Clearly, TSN features must be maintained when moving a communication flow from one link to another. The objective of this activity is to address such a challenging scenario and the behavior of KPIs such as packet loss, latency and jitter that may be, in principle, impacted by the flow switching. The activity will be mainly experimental.

Some very preliminary tests have been carried out in the setup reported in Figure 13. Two mini-pc Intel NUCs were connected by two different links, one wired (Ethernet) and the other wireless (Wi-Fi). Synchronization was achieved by running the IEEE 802.1AS protocol on the wireless link.

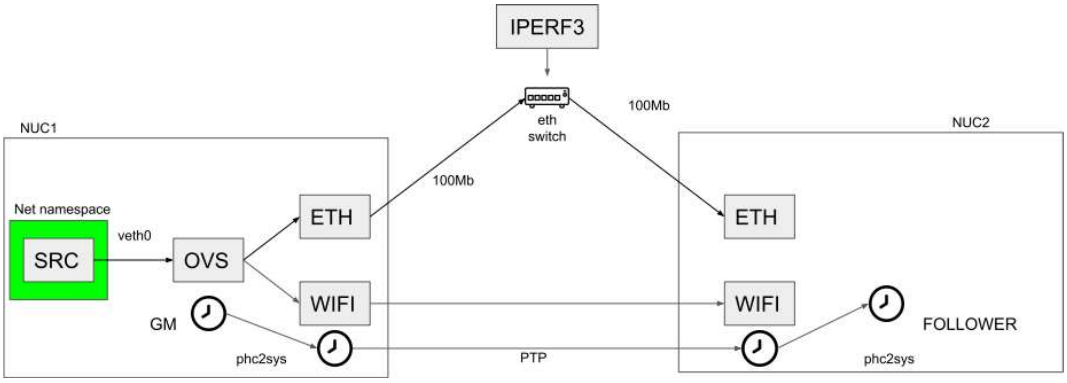

Figure 13 Experimental setup

In UC1, Open vSwitch was installed handled by a SDN controller. In the setup, a communication flow was implemented on the Ethernet link generated by an application running on NUC1 that cyclically sends frames to NUC2. At a certain point, such a link started to be influenced by an interfering traffic, generated by the network tool iperf3. Therefore, the latency on the wired link progressively increased up to overcoming a threshold, set to 45 ms in this case. At that point, the controller detected the anomaly and routed the flow on the Wi-Fi link. The behavior of the latency is shown in Figure 14.

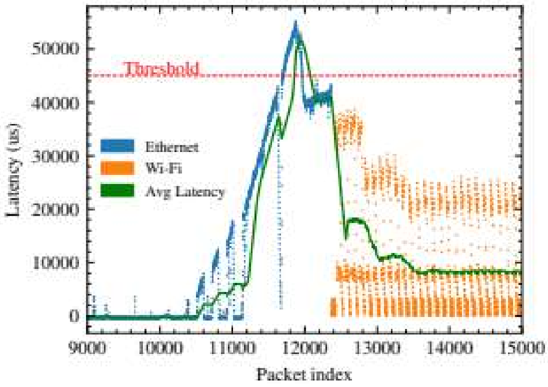

Figure 14 Latency behavior

The switching of the communication flow was seamless since no packet loss was detected. Concerning the latency, it was considerably reduced on average, even if non negligible fluctuations were permanently observed, with the consequent impact on jitter. A subsequent analysis showed they were caused by the wireless interface of NUC1 that periodically entered the power saving mode, forcing the packets generated by the application to be buffered and hence to be transmitted with unpredictable delays.

The obtained results are interesting since they confirm the feasibility of the proposed approach. However, several other activities are envisaged. The most relevant ones are listed below:

- Switching of the communication flow from the Wi-Fi link to the Ethernet one.
- Assessment of the IEEE 802.1Qbv behavior (this was not tested in the experiments).
- Use of different SDN controllers.
- Assessment of the TWT behavior.
- Investigation of more complex scenarios.

4.4.4 TSN redundancy

Path diversity can play an important role in providing deterministic communication services. The standard IEEE 802.1CB defines the TSN redundancy capability, to allow to transmit information through multiple paths. This redundancy can be used to increase the resilience of the network against interference and/or malicious attacks, as well as to improve the mobility of end-users towards a seamless roaming experience.

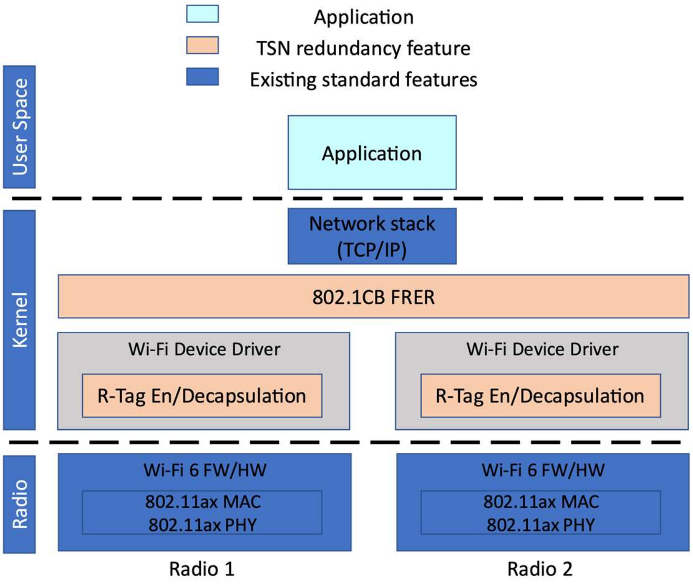

Figure 15 Path diversity (802.1CB) in Wi-Fi 6 TSN using two radio NICs

We have published a study [26] on how to take advantage of the TSN redundancy capability (as defined in the IEEE 802.1CB standard) to eliminate outages or delays due to events like roaming and interference in a mobile robot use case enabled by Wi-Fi 6 TSN. Demonstrating the roaming performance with no delay impact on the applications though simulations of a mobile robot in a factory scenario and experimental results with a mobile robot connected via multiple Wi-Fi 6 radios in a warehouse environment. Figure 15 illustrates the communication stack, and Figure 16 shows the results in latency when using redundancy vs when not using redundancy.

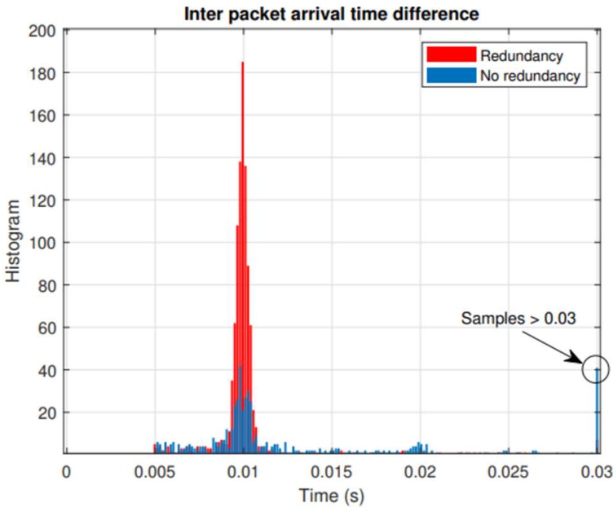

Figure 16 Inter packet arrival times w/o redundancy enabled. We observe most packets arriving near 10 ms intervals with redundancy, however a large group of packets arrive with significant delays greater than 30 ms when redundancy is not enabled.

The Wi-Fi 7 multi-radio/MLO (expected to be available in 2024), provides another mechanism for path diversity, but managed at the MAC layer, allowing to use a single network interface instead of multiple ones. We plan to evaluate the upcoming MLO feature for seamless mobility and compare it to the current state-of-the-art alternative of multiple NICs.

4.5 Scheduling techniques and queueing models with mixed traffic classes

Traditional strategies in the handling of traffic flows in respect to the allocation of queuing resources assumes a small portion of high priority traffic, e.g., voice, requiring preferential delivery with respect other flows in the network. Thus, voice, as well as few other services (e.g., network control, signaling, etc.) have been typically classified as Expedited Forwarding (EF) traffic class according to the Differentiated Services (DiffServ) scheme [27] for per-hop behavior. Then, the largest portion of queuing resources have been classically devoted to less prioritized flows.

Now, when facing the introduction in the network of deterministic services as new source of flows together with the traditional ones, it is of high interest to understand how deterministic flows will co-exist, especially in situations where the deterministic traffic can represent a very high component of the overall traffic in the network. A representative case is provided e.g., by fronthaul traffic as the one leveraging on 802.1CM TSN profile, requiring of high throughput and extreme low delay and latency. For instance, Figure 17 presents an example of a QoS model with multiple priority queues described in [28].

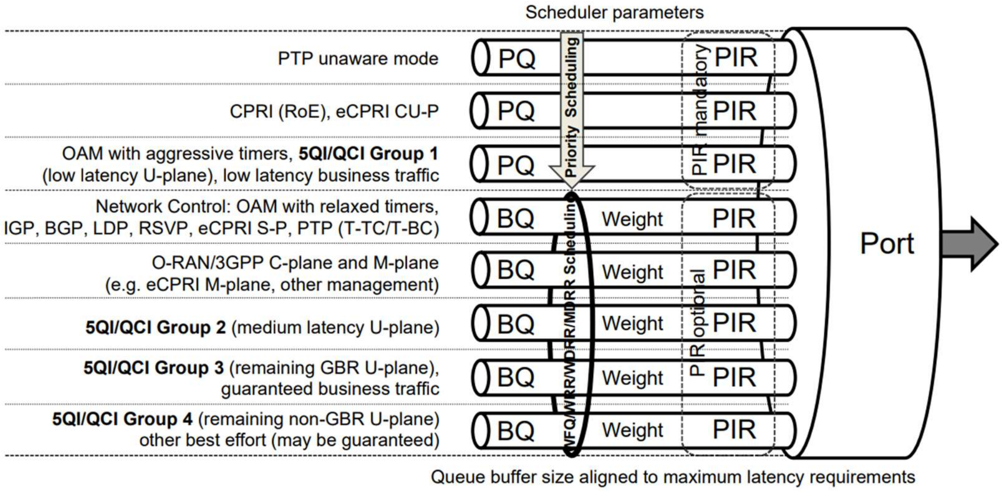

Figure 17 Example of QoS model [28]

Deterministic services not always will have the requirement of low latency and jitter and/or high throughput. The characterization of deterministic services in PREDICT-6G [1] is an example of this. However, the need of understanding the flow dynamics in respect to the queueing allocation is yet relevant when co-existing with traditional flows.

In consequence, the analysis and definition of proper scheduling strategies in scenarios combining deterministic traffic with current kind of flows is essential to define and provide guidelines in operational networks. In principle, the objective is to work with different simulations, with potential implementation in real systems for validating the previous analysis.

4.6 PDU Sets and Multi-Modal Data Flows in TSN-Enabled 3GPP Networks for Location and Sensing

3GPP Rel.18 introduced support for Extended Reality (XR) sessions and Packet Data Unit (PDU) sets allowing the system to serve different QoS-sensitive service flows to a single or multiple UEs that are collectively participating in a single application. XR essentially defines a mix of traffic flow categories that form a single service offering to one or more 3GPP-enabled UEs, i.e., audio, video and haptics. This mix of traffic flows is also referred to as multi-modal data flows which form a single service. Over time, each multi-modal flow creates differently sized data units on the application layer which are chunked into network-layer PDUs (if an application layer data unit is larger than a network-layer PDU). Consequently, PDU Sets define the ability of a 5G network to understand which PDUs belong to an application-related data unit. Only if the PDU set is successfully delivered the data unit can be used for further processing by the application. For instance, if the PDU Set forms a video frame or a sensing data result, the 5GS can ensure the correct delivery of the PDU Set and apply potential re-delivery of PDUs within a PDU Set. If for any reasons the 5GS must drop packets to deliver on the indicated 5QIs, it would be advisable if entire PDU Sets are dropped to free up resources for other PDU Sets to be delivered in their entirety. Such reliability feature in relation to TSN-based PDUs is an important enabler for integrating a DetNet data plane over an 5G Advanced mobile network.

Figure 18 illustrates the Rel.18 features PDU Sets and Multi-Modal Data Flows, as described in [29] and considered for implementation in the Localization and Sensing use case, described in D1.1 [1]. Moreover, [29] also introduces the concept of Multi-Modal Data Flows, which allows the 5GS to identify inter-related QoS flows distributed across multiple UEs that are serving the same application. For instance, if QoS Flow 1 is radar sensing data and QoS Flow 3 video sensing data, the 5GS can ensure that both flows are treated as a Multi-Modal Data Flow for combined consumption of an ML-based analytics engine that processes the sensing data.

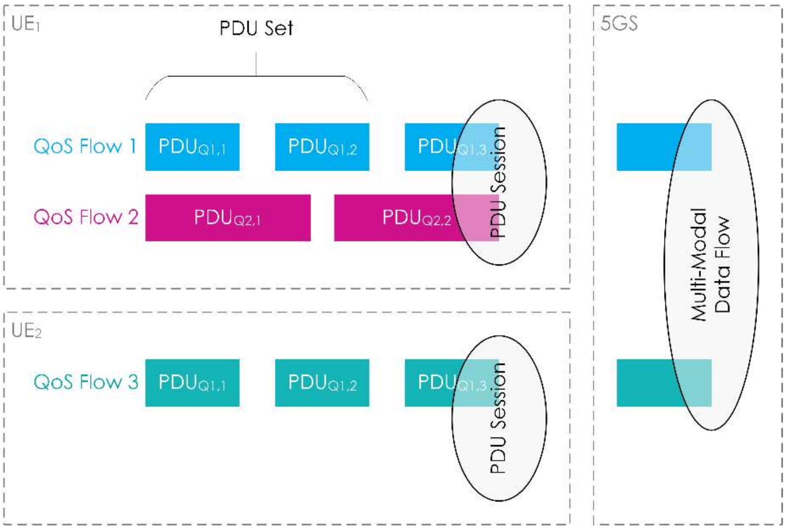

Figure 18 Considered Rel.18 Features PDU Sets and Multi-Modal Data Flows for Localization and Sensing PoC

For instance, sensing data formats can range from pure text-based periodic short bursts of numeric values to actual video streams for machine-based processing. All sensing data collectively forms the input to the algorithm that determines the sensing result, while the core network is chartered with processing the sensing data, following 22.837's proposition. Each sensing data type (numeric vs video) will have its own QoS Flow with different QoS requirements (5QIs) and the set of these QoS Flows form the sensing service. In PREDICT-6G, this Rel.18 feature is bundled with an underlying TSN-enabled Ethernet PDU session which implements an DetNet-compliant Data Plane.

The protocol stack of the User Plane is provided in Figure 19, illustrating the TSN extension 802.1q within a standard 802.3 frame with an IPv4 payload. SDAP, PDCP and RLC are illustrated on the Uu interface between the UE and the gNB which realize PDU Sets and Multi-Modal Data Flows via information stored in the header fields of SDAP, PDCP and RLC. The coordination of TSN-based traffic of applications in combination with 3GPP (TR 23.700[29]) features such as PDU Sets and Multi-Modal Data Flows will be studied and integrated in this activity.

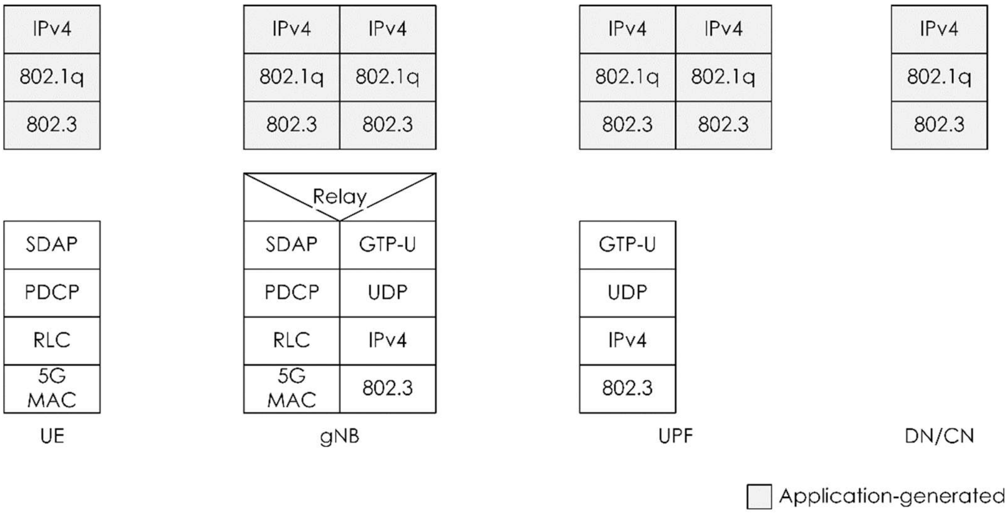

Figure 19 Considered Protocol Stack for Localization and Sensing PoC

4.7 Non-deterministic devices and networks

PREDICT-6G will provide E2E deterministic paths for services spanning through multiple heterogeneous network domains and technologies. Most of the domains targeted by PREDICT-6G (e.g., 3GPP domain, DetNet/IP domain) implement deterministic network capabilities, which are leveraged by the PREDICT-6G control and management plane through the Open APIs (see Section 6) to compose and assure E2E services. In some cases, however, PREDICT-6G's E2E service needs to extend over domains that lack inherent deterministic capabilities, e.g., by only providing best effort services over a routed IP network. Such network segments may still need to be integrated in PREDICT-6G's E2E service as either they are the only available domains through which two deterministic network segments can be physically connected, or there is a demand to connect to legacy devices with no deterministic capabilities either in the devices themselves or in the last mile connecting them to the first deterministic device.

To provide E2E determinism in the MDP, several enablers need to be supported both on the device-side (i.e., at the communication endpoints) and on the network-side (e.g., intermediate routers, links) that comprise the network infrastructure.

On the device-side, the required determinism needs to be in harmony with the internal organization and scheduling of the device's hardware and SW stack, including passing through virtualization layers (if present), the scheduling of applications and processes, network traffic generation, I/O scheduling, buffering and cross-layer data transfer until the point of releasing packets at the device's network interface.

On the network-side, in each hop along the E2E path is responsible to provide the right level of deterministic and predictable transmission opportunity, bandwidth, buffering delay, propagation delay, zero congestion loss, etc. Additionally, cross-domain interworking must be implemented at the border of the network domains.

In the following, we detail the duality of emulating some level of determinism over inherently non-deterministic devices and network segments.

4.7.1 Device-side requirements and considerations

At the end devices, deterministic data generation may receive interference from multiple sources − including application, kernel, NIC, virtualization layers, etc. − along the device internal traffic flow from program code to transmission on wire or via waveform. This is especially relevant for devices that are multi-purpose general computers simultaneously running multiple workloads and having a deep SW stack between the network HW and the applications, and less of a problem for a single-purpose HW/firmware based fully regulated device. However, with the penetration of digitalization and virtualization to every industry, it is expected that deterministic services will increasingly terminate at such multi-purpose (even virtualized) devices with applications rather than HW-based appliances.

Figure 20 shows the schematic design of a device illustrating the process of data generation. In brief, the process of data generation consists of the following steps. In Step 1, the operating system's process scheduler triggers the execution of the application process. In Step 2, during the execution of the process, the program code obtains data, and in Step 3 the data is transferred to the buffer of the kernel's network stack. The kernel transfers the data from the network stack's buffer to the NIC's own HW transmit buffer in Step 4, from where the NIC device driver sends data out on a network port according to the network technology's media access procedures in Step 5.

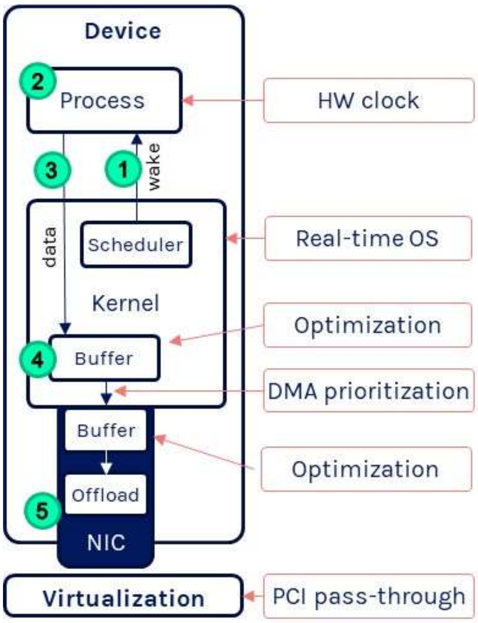

Figure 20 Process of data generation in a device

To enforce the data transmission pattern assumed or required by the application process, the kernel may need to be equipped with deterministic process and I/O scheduling capabilities to minimize the internal jitter that may otherwise modulate on the data pattern before it leaves the premise of the device. First, the clock accuracy plays an important role during data generation inside the device, as well. Resource sharing and data buffering are also threats to determinism. In Step 1, the OS process scheduler may introduce jitters in process execution that impact how data is transferred to the OS network stack in Step 3. To eliminate this risk real-time kernel may be needed with execution guarantees (e.g., by CPU affinity, pinning, interrupt masking, etc.). Clock inaccuracy (drifts, jitters) may cause the application process to trigger data transfer at irregular interval in Step 3, even though the program code is supposed to produce data at deterministic periods in Step 2. The application of HW clock in the device may be solve these problems. The buffering in network stack may need to be turned off or the buffer handling may need to be optimized in the kernel. In Step 4, the transfer of data from network stack to NIC memory may be delayed due to memory channel contention. This risk may be eliminated by DMA prioritization. In Step 5, the NIC and its firmware may introduce buffering, various TX offload, etc., which need to be limited, completely switched off or a NIC with such guarantees must be used. Virtualization layers, especially when the process executed in a VM, may introduce further non-determinism into the entire stack, which requires the application of PCI passthrough to access NIC from VM.

Taking the above considerations by the proper configuration of the components and internal mechanisms and the upgrade of possible non-deterministic components (e.g., kernel, memory, NIC) the determinism of data generation could be guaranteed in most cases. However, there could be devices with no native support for determinism, e.g. legacy industry devices (robots, sensors) with non-configurable components or non-replaceable/non-extendable components and interfaces.

In this case, a possible solution could be the application of a deterministic, TSN-capable next-hop router or aggregator GW between the network interface of non-deterministic device(s) and the network as shown on Figure 21. The utilization of next hop router is recommended in case of a standalone device, while an aggregator GW may be useful, where the traffic of more devices (e.g., sensors) may be aggregated to a single deterministic data flow. To provide the highest level of determinism, the device's components and internal mechanisms should be configured to support the maximum deterministic data generation, (with the previously introduced considerations) and additionally, the communication link (and its scheduling) between the device and the router/aggregator GW should be configured also to support the maximum determinism. The deterministic capabilities should be measured (e.g., through the KPIs established in Section 3 of D1.1 [1]), profiled and reported to the AICP so that it can consider the achievable level of determinism and validate E2E service requests targeting these devices.

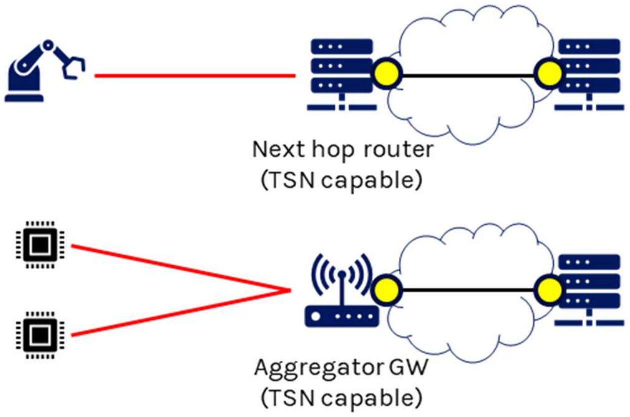

Figure 21 Potential solution to support determinism for non-deterministic devices

4.7.2 Network-side requirements and considerations

Several requirements must be fulfilled to provide E2E determinism at the network-side of a service. One of them is the per hop deterministic scheduling, both inside the network domains and in the edge of the domains. For deterministic scheduling, the support of time sensitiveness is mandatory in the network domain. To provide reliability PREOF and path control and reservation mechanisms (via admission control) should be supported. At the border of network domains proper cross-domain interworking should be implemented:

- to harmonize of intra-domain service configuration (e.g., scheduler parameters, bandwidth allocations, delay budgets, etc.).
- to support proper cross-domain path selection and path capability configuration to match with the E2E service requirements.
- to support cross-domain PREOF inter-working.

In a non-deterministic network domain, where one or more from the above requirements could not be supported by the applied L2/L3 technology, other mechanisms should be used to enable the interworking between deterministic and non-deterministic network domains to guarantee E2E determinism for services. For cross-domain interworking a proper solution could be the measurement and profiling of the intrinsic QoS capabilities of the non-deterministic network domain and the detection of the load and congestion points where buffering/queueing starts to build up congestion delays or even early packet discards inside the domain. Based on the measured latency, throughput, packet loss and jitter characteristics, the sustainable load vs. the achievable KPIs and their determinism could be modelled and reported to the AICP.

In addition to the measurement and profiling, the existing QoS mechanisms (if any) of the network domain should be also leveraged by the MDP to meet the offered deterministic guarantees (e.g., mark all deterministic traffic as Strict Priority, configure the WFQ weights, etc.). For this purpose, admission control may be enforced to limit the amount of traffic entering domains with no or limited deterministic capabilities up to the level for which the domain's intrinsic level of determinism can still be provided.

4.8 Industrial cross-domain TSN

In PREDICT-6G Deliverable 1.1 [1], we included the Smart Factory use case (UC), where GESTAMP exposes the evolution of an industrial use case towards the virtualization. In the UC, part of the logic that controls robotic elements and runs in Programmable Logical Controllers (PLC), is offloaded to the cloud by using virtual PLCs. That will require a Deterministic Network to ensure the order of the command received by the robotic elements and to guarantee a minimum packet lost.

Taking this UC as reference, the Industrial Cross-Domain TSN cluster of activities aim to build an E2E demonstration of Smart Factories using multiple domains: 3GPP mobile network, Wi-Fi, and fixed network, all of them integrated and coordinated by the PREDICT-6G Control Plane (AICP). The integration of the multiple domains might also imply the use of a non-Deterministic network, with the goal of stressing the Control Plane. In the following subsections, we describe the different activities that compose the Industrial Cross-Domain TSN.

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4.8.1 TSN support in 3GPP networks

As mentioned in the introduction of this section, the support of TSN in the 3GPP network was defined in the Release 16 of the 5GS System Architecture standard (TS 23.501 [17]). As described in Figure 22, 3GPP defines a way of integrating the 5G System as TSN bridge by using new components in the border of the network, called TSN translators, one in the UE side (Device-Side TSN Translator) and another one in the DN side (NetWork TSN Translator). The main objective of the TSN Translators is to integrate the 5G System as a TSN bridge with other TSN networks or systems, enabling the integration of 5GS within the Industrial communications.

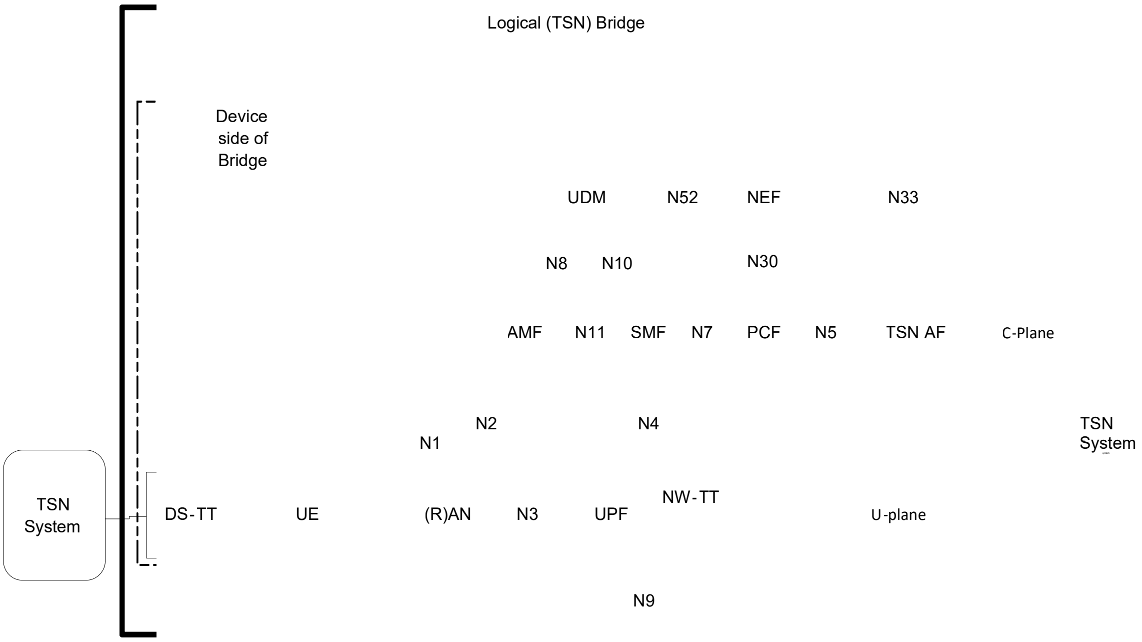

Figure 22 5GS System Architecture for TSN

Our vision of TSN in 3GPP networks is summarized in Figure 23, where we show how TSN involves four pillars that are crucial for PREDICT-6G project: Reliability, Time Synchronization, Traffic Shaping (time sensitiveness) and Resource management. That defines the main research lines in this area, which include the research in new time-based schedulers for 3GPP networks, the frame replication, and the time synchronization through 3GPP wireless networks.

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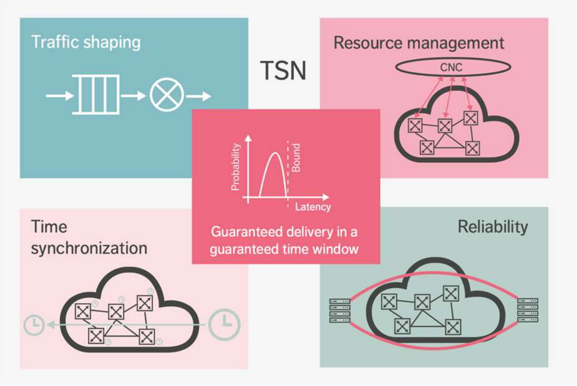

Figure 23 Valuable tools within the TSN toolbox that enable deployments in industrial automation [30]

The goal is to integrate the Smart Factory use case described in the Deliverable 1.1 [1] in a multi-technology demonstration, described below. Figure 24 describes the status of Smart Factory use case at 5TONIC open lab, which includes the integration of the use case with a 5G network with TSN capabilities. The main innovations are:

- TSN translators in Device Side (DS-TT) and Network Side (NW-TT): The translators are developed on top of a SW switch that provides L2 bridging capabilities.
- On top of the TSN Translators, we develop a version of 802.1Qbv [16] scheduler, with support to multiple gates and guard band.
- To supply an alternative to PDU session of type Ethernet, which cannot be tested as there are no commercial UE available with that support, the TSN Translator enables the extension of a L2 network though the 5G System by creating a VxLAN underlay network.

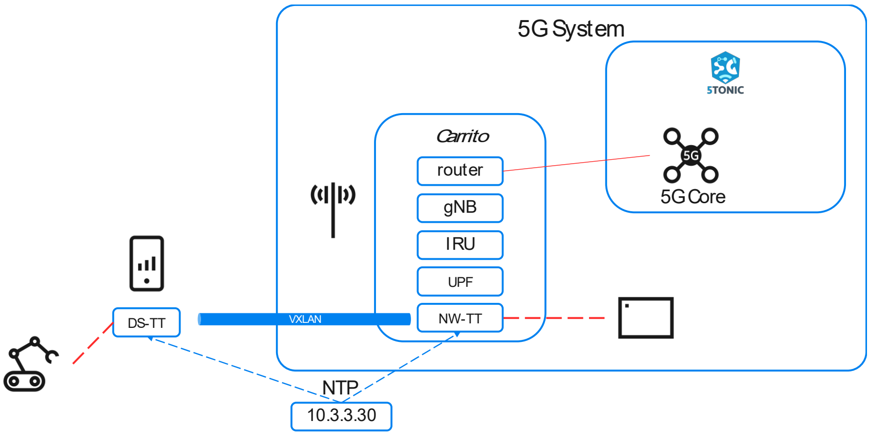

Figure 24 Current status of Smart Factory at 5Tonic

With this setup we can simulate the Smart Factory use case at 5Tonic. In the roadmap, we explain the next steps planned for this year: do a complete test of the use case with time-based schedulers and add frame support to the solution.

4.8.2 TSN support in WI-FI networks

This activity aims to integrate the research and innovation activities from TSN on WI-FI cluster into the multi-domain infrastructure deployed at 5TONIC laboratory. For that, we will replicate at 5Tonic the basic Wi-Fi infrastructure used in TSN on Wi-Fi, which will be the basis for integrating any of the innovations coming from TSN on Wi-Fi. For next Delivery we aim to have the requirement analysis for this integration as well as a solution for integrating 5Tonic TSN Wi-Fi with the PREDICT-6G AICP.

4.8.3 Linux-based TSN Switch

The field of TSN lacks an open-source, real-life implementation of a TSN-capable switch that provides the necessary flexibility and control for researchers to test and develop new technologies and algorithms. To address this problem, we propose developing a TSN-capable switch that leverages AF_XDP and eBPF technologies to achieve reliability, speed, and flexibility. By combining AF_XDP and eBPF, our solution aims to provide researchers with a powerful and efficient platform for TSN research and development.

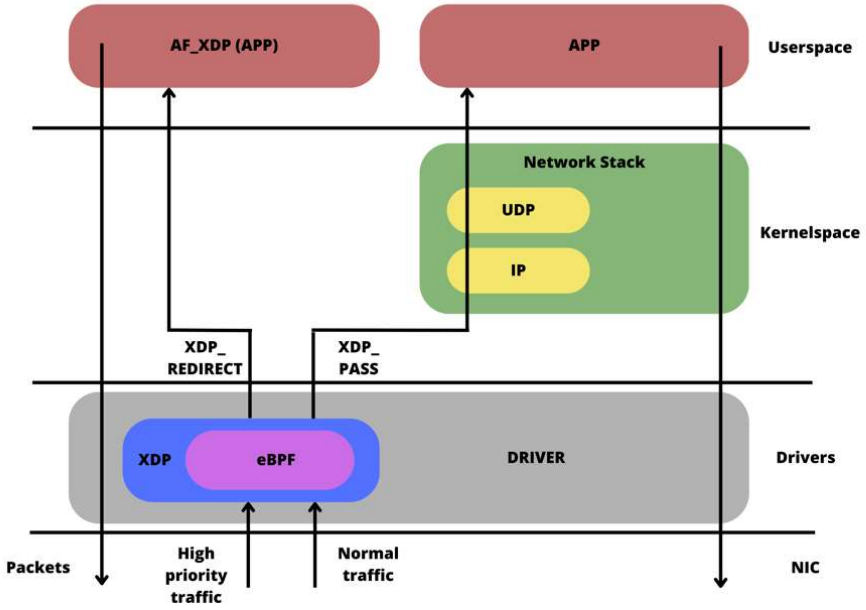

Figure 25 TSN Capable Switch architecture

As shown in Figure 25, packets arriving at the interface are filtered and intercepted, to then be redirected directly to the user plane, bypassing the kernel, where we will handle the processing and forwarding or passed to the kernel to be handled normally.

In the upcoming year, our focus will be on implementing and testing different queuing disciplines based on the latest TSN standards, such as 802.1Qbv. We will utilize eBPF and AF_XDP to attach and detach filters, allowing us to customize the scope of network traffic capture as desired. By experimenting with various queuing algorithms, we aim to optimize the switch's performance for different scenarios and applications.

Additionally, we will work on integrating WLAN (Wireless Local Area Network) capabilities and DS/NW-TT (Deterministic Networking Traffic Type) support into our switch.

Our TSN-capable switch is expected to offer a range of features to facilitate TSN research and development. Some of the possible expected features include:

1. Deterministic network behavior: The switch will enable researchers to achieve deterministic handling of network packets by minimizing overhead and latency using AF_XDP and eBPF technologies.
2. Full control and customization from UP: Researchers will have complete control over the system capabilities, allowing them to fine-tune the switch's behavior according to their specific requirements.
3. Open-source implementation: Our solution will be open-source, encouraging collaboration and contributions from the TSN research community.
4. Integration with WLAN and DS/NW-TT support: We aim to integrate WLAN and NW-TT capabilities into the switch, enabling researchers to experiment with TSN in wireless networking environments and develop new deterministic networking technologies.

4.8.4 Multi-Domain Integration

To test the multi-domain multi-technology data plane, we aim at developing a complete E2E prototype integrating several technologies and potentially different administrative domains. The final objective of this Task will be to implement an MDP like the one sketched in Figure 26. This figure presents the physical implementation, and the expected components at L3 and L2, including multiple TSN-enabled technologies (Wi-Fi TSN, IEEE 802.1 TSN, and 3GPP TSC) together with a non-deterministic island. The clients are expected to be composed of a DT and the corresponding physical robot which the digital twin controls.

Focusing on Figure 26, the physical infrastructure will run in hardware deployed in 5TONIC, including commercial off-the-shelf TSN switches and Linux-based TSN switches and access points.

An E2E deterministic network requires of coordinated operation at L2 and L3 levels. In terms of L3, we will use the DetNet protocol. Figure 26indicates the points where we will need to perform DetNet encapsulation and forwarding. As shown in the figure, we will have multiple DetNet hops, and within the 3GPP domain, we will implement PREOF by leveraging in multiple DS-TT and NW-TT devices connected to the 5G SA available in 5TONIC.

To support extended time bounded operation and showcase the interaction between DetNet and IEEE 802.1TSN, we show in Figure 26, the L2 view of the network. This view showcases a L2 IEEE 802.1TSN cloud which will be used to provide L2 FRER to the communication.

Finally, one of the endpoints will implement a non-deterministic network, to showcase possible technologies to be developed in this area by the project.

This very challenging setup requires of contribution from multiple partners, including:

- TSN extensions to IEEE 802.11, as developed in sections 4.4 and 4.8.
- XDP-based IEEE 802.1 TSN switch as developed in section 4.8.
- DS-TT and NW-TT together with the 5G TSC, as developed in 4.8.
- Support of non-deterministic islands, as described in 4.7.

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- A DetNet compatible data plane, which will be described in the following.

Within this task, one of the main activities to be performed is the development of a DetNet compatible data plane. Currently UC3M is developing a prototype, employing P4, to perform encapsulation in the MPLS option described in DetNet specification (PREOF including a local process in charge of buffering and reordering). This prototype runs in local virtualization environment, simulating a P4 switch. Current development is limited to this environment, and it is needed to understand how to run it in a physical P4 switch or if it is not possible, to run it on top of an XDP-based P4 data plane. The reason for this need, is that the current P4 implementation, as described above, requires of a local process to do reordering, since P4 has a limitation on buffering (it cannot be done). Therefore, we need to find a solution to run the reordering function in Linux-based machine or in local switch processing space.

During the first year, this task will focus on each of the components, developing the initial version of the TSN extensions to IEEE 802.11, the XDP-based L2 IEEE 802.1TSN switch, the initial version of the DS-TT and NW-TT and developing the DetNet data-plane. This first year will then focus on understanding each element and start analyzing the changes required to integrate all under the common umbrella of the DetNet protocol. Also, this task will provide input to Task 2.2 and WP3, regarding the possible control mechanisms available.

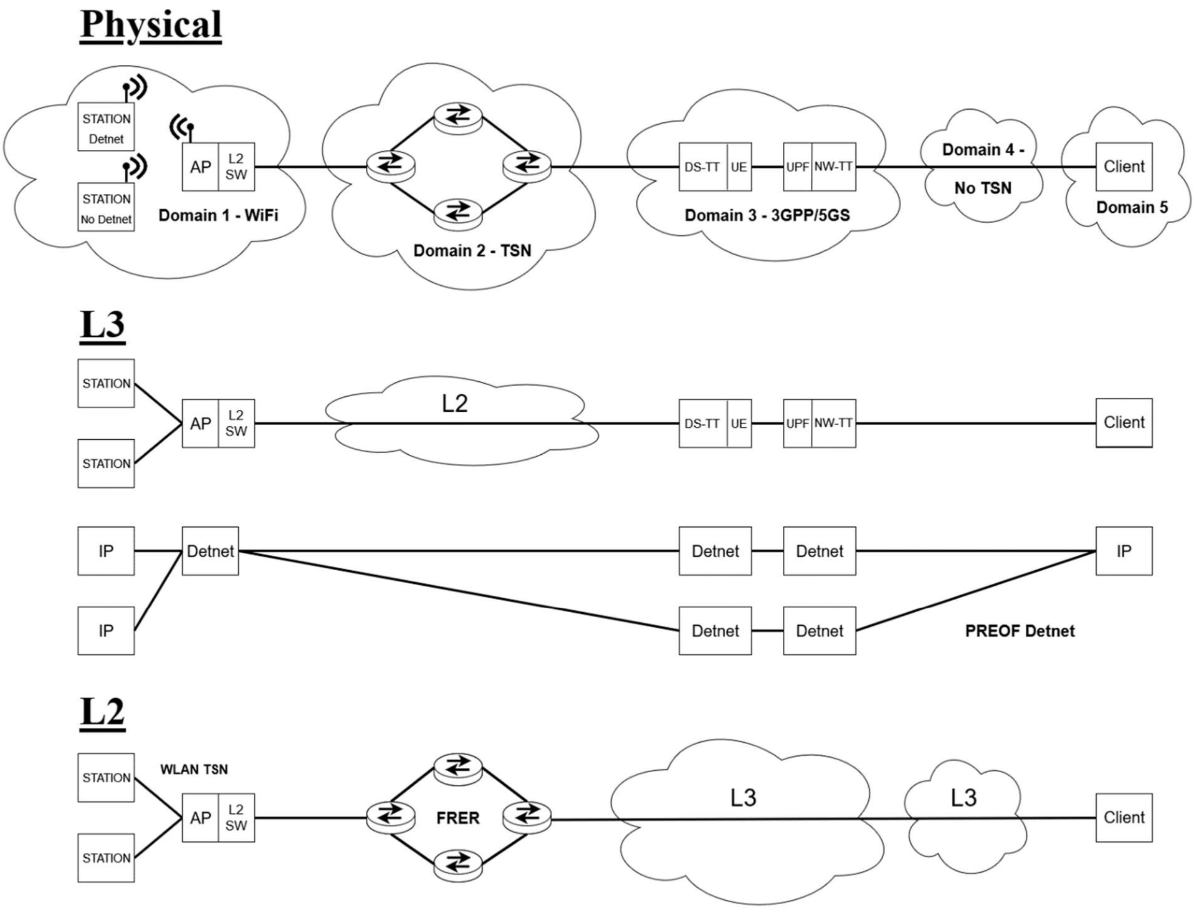

Figure 26: MDP development in 5TONIC

5 Detnet/RAW Domain integration

5.1 Introduction to Detnet and RAW

The **Deterministic Networking (DetNet)** WG focuses on deterministic data paths operating over L2 and L3 segments to provide predictable latency, loss, and packet delay variation. It collaborates with IEEE802.1 TSN to establish a common architecture for both layers. Applications benefiting from deterministic networks include audio/video systems, transportation multimedia, and industrial applications. The initial focus is on networks under a single administrative control or closed groups, excluding large-scale domains like the Internet.

The WG is responsible for the DetNet architecture and specifications covering data plane, Operations, Administration, and Maintenance (OAM), time synchronization, management, control, and security. It enables multi-hop paths with controlled latency, low packet loss, and high reliability for both unicast and multicast flows. The work involves flow characterization, frame encapsulation, forwarding behaviors, and potential state establishment in intermediate nodes. Supported L3 technologies include IP, MPLS, and L2 encapsulations like pseudo wires and GRE tunnels.

The WG documents which deployment environments and types of topologies are within (or outside) the scope of the DetNet architecture. Their work focuses on the data plane aspects and is independent from any path setup protocol or mechanism. DetNet will also document DetNet Controller Plane approaches that reuse existing IETF solutions, such as Path Computation Element (PCE), and identify the WG responsible for any extensions needed to support DetNet. Documents produced by the WG will be compatible with the work done in IEEE802.1 TSN and other IETF WGs. Their scope generally excludes modifications of transport protocols, OAM, L3 forwarding, and encapsulations, but it may discuss requirements for such modifications and the work will be coordinated with the WG responsible person for the technology.

The **Reliable and Available Wireless (RAW)** initiative aims to enhance the reliability and availability of IP connectivity over wireless networks. It extends the concepts of the DetNet WG to address the challenges of wireless communication, such as low packet error rate, bounded consecutive losses, and bounded latency. RAW focuses on new wireless applications, including Aeronautical Data Communications, as well as industrial, pro audio and video, gaming, and edge robotics. The group aims to identify areas where adaptations of DetNet and other IETF technologies are needed, while also examining the relevance of existing IETF work. RAW collaborates with other WGs to review solutions for deployment challenges and aims to provide timely solutions for these industry applications.

The RAW WG operates within a short timeframe of 12-18 months and aims to promptly address the needs of new wireless applications. The initial milestones include publishing Informational documents on Use Cases, Requirements, Architecture/Framework Aspects for a Wireless Network, and an Evaluation of Existing IETF Technologies and Gap Analysis. RAW seeks input on deployment plans, requirements, operational practices, and additional supporting mechanisms. While RAW is not responsible for developing solutions, it may coordinate with the IESG to determine where solution work will be done. The group closely collaborates with the DetNet and its work may be of interest to other SDOs, such as 3GPP, IEEE, and the Aeronautical industry.

5.2 Mobility problem statement

Wireless communication faces challenges due to shared medium and unpredictable interferences. RAW aims to achieve deterministic networking in wireless environments by ensuring high reliability and availability for IP connectivity over wireless networks. RAW addresses the difficulties of achieving deterministic properties such as low packet errors, limited consecutive losses, and bounded latency in wireless medium. It extends the concepts of the DetNet WG to provide reliability and availability for IP networks utilizing scheduled wireless segments and other media resources like IEEE Stds. Similar to DetNet, RAW focuses on L3 aspects to support applications that require high reliability and availability, while abstracting the underlying radio layers.

There are several use cases where reliability and availability are key requirements for wireless heterogeneous networks. One example is XR applications, such as for example immersive gaming, DTs, etc. In these environments, UEs demand strict and predictable behavior, in terms of latency and/or resilience and/or availability and/or throughput, while they move and might change its point of attachment.

RAW focuses on separating the time scales of path computation and path selection. It operates at the path selection time scale, where the forwarding decision is made for individual packets. The main objective of

RAW is to choose the most suitable solution among multiple redundant options proposed by the **Path Computation Element (PCE)** for each packet. This ensures a Reliable and Available service while minimizing the inefficient use of limited resources. To achieve this, RAW introduces the **Path Selection Engine (PSE)** as a counterpart to the PCE. The PSE enables rapid local adjustments of forwarding tables within the diversity selected by the PCE for the Track. It allows the utilization of advanced forwarding techniques such as **Packet (hybrid) ARQ, Replication, Elimination, and Ordering (PAREO)**, as well as scheduled transmissions on a faster time scale.

Control plane solutions need to cope with mobility, by proactively preparing the network for the change of point of attachment of the UE, and the impact that this has in terms of new sub-tracks used for the traffic. This requires inter-PSE coordination for the preparation of the handover. L2-specific extensions can be used to aid the UE determine where to roam to if stringent conditions need to be maintained (requiring RAW support). Current RAW and DETNET solutions are limited to static scenarios, where neither the end nodes/UEs or the internal/local network nodes move.

5.3 Multidomain extensions for Detnet/RAW

There are also situations where hosts are connected to different RAW domains and need to communicate with reliability and availability guarantees. These scenarios occur in large factories with multiple network domains (per production lines or buildings/sites), residential environments with different networks (e.g., home and garden), or vehicular settings where hosts are connected to different vehicles.

In a multidomain communication scenario involving multiple RAW domains, inter-PSE coordination mechanisms are needed. Although there are existing inter-PCE solutions for learning inter-domain paths, they are insufficient for guaranteeing Service Level Agreements (SLAs) across domains. The PSE of one domain lacks full visibility and control over other domains, limiting its capability to ensure reliability and availability. Therefore, there is a need to redefine mechanisms for inter-PSE coordination across domains.

Standardized solutions like the Hierarchical Path Computation Element (G-PCE) can compute multi-/inter-domain paths. In this approach, a parent PCE maintains a domain topology map with information about child domains and their interconnections. However, the parent PCE does not have knowledge of resource availability or connectivity details within the child domains due to confidentiality requirements and scalability issues. Instead, child PCEs handle intra-domain path computation based on their own domain topology information.

While solutions like the G-PCE are a step in the right direction, they are not sufficient to solve the multi-domain RAW problem. PSEs require additional information from other involved domains to effectively respond to transient changes and ensure reliability and availability in a heterogeneous wireless mesh network spanning multiple domains.

The PSE can be implemented as a distributed functionality, where each RAW router along the path makes forwarding decisions based on local and OAM information. Alternatively, the PSE can be centralized and performed by the entry (ingress) router in the domain. In cases where there are multiple ingress nodes, there can be multiple PSEs, and the ingress router then carries out source routing based on the decisions made by the PSE.

In scenarios involving multiple interconnected RAW domains, relying on independent RAW solutions within each domain is inadequate. To effectively address the challenges, PSEs across domains require global E2E information and the ability to implement OAM mechanisms. These OAM mechanisms, as described in the RAW OAM Support document[5], enable the monitoring of the selected paths' quality. By having access to comprehensive information and employing OAM techniques, PSEs can ensure the reliability and performance of the selected paths throughout the entire network, spanning multiple domains.

6 Programmability and open APIs

PREDICT-6G was designed with a modular architecture (see section 9 of D1.1 [1]) where any number of network technologies (referred to as domains) can be integrated to provide E2E services with deterministic guarantees. This flexibility is realized by means of domain abstraction and domain programmability. Domain abstraction means to hide the technology specific mechanisms from the PREDICT-6G's E2E deterministic service management scope, so that technical complexity does not prevent scaling the architecture to deployments with a variety of heterogeneous technology domains. Therefore, domains are controlled by their respective Management Domain (MD), which integrate with domain technology specific APIs and interfaces on their South-bound interface, and provide uniform (i.e., technology agnostic) services towards the E2E MD [1]. This section provides requirements, methodology and insights on the South-bound integration of technology specific MDs.

6.1 The scope of Open APIs

PREDICT-6G's overall goal within the control and management plane is to automate the provisioning and fulfillment of deterministic services through: (1) composition of E2E services from domain specific services; (2) closed-loop domain specific controller actions to maintain the QoS within each domain boundaries, and (3) closed-loop E2E service management actions to maintain the service in the E2E and perform conflict avoidance or resolution across domains. All these actions require interaction between PREDICT-6G's control and management plane (AICP) and its Multi-technology multi-domain Data Plane (MDP). In that regard, the MDP will define Open APIs at the boundaries of the MDP and AICP, that is, APIs that expose services of the MDP to be consumed by the technology specific MDs of the AICP. The scope of the Open APIs includes the followings:

1. Expose the deterministic capabilities of each technology domain.
2. Expose control points through which data-plane mechanisms may be dynamically programmed to achieve determinism for the current and predicted deterministic service flows.
3. Provide means to collect data-plane measurements quantifying the state of the flows, resources, services, and the level of the achieved quality of service and deterministic targets.

Note that the PREDICT-6G's MDP is a non-conventional data plane (as opposed to, e.g., the data plane of a 3GPP network) in a sense that PREDICT-6G builds a network of systems rather than a network of user plane devices. Therefore, from programmability perspective, the data plane of PREDICT-6G consists of full-fledged networks that bring not only their user planes (which will be the plane where actual data packets are transferred in E2E) but also their own control/management planes and interfaces into the MDP. Consequently, the configuration and programming of the E2E's constituent networks requires that the MDP integrates with the existing C/M-plane mechanisms and interfaces of said networks, whenever such mechanisms and interfaces exists. For technologies with highly advanced standardization and long-time experience of large-scale commercial deployments, such as 3GPP networks, control and management mechanisms have been already existing as standards. Yet to bring deterministic requirements under control, the existing means of network monitoring and control may still need to be extended by PREDICT-6G. For other technologies where the industry has less experience of wide-scale deployment and operation (e.g., IETF DetNet of deterministic Wi-Fi), the level of network programmability is usually lower and significant gaps may exist that needs to be filled by PREDICT-6G MDP innovations. Finally, for network segments with no deterministic capabilities at all, the full stack of management may be missing and therefore PREDICT-6G needs to create novel mechanisms for their programmability (including monitoring as well as configuration and actions delivered in their user plane). Such novel mechanisms may include the creation of new U-plane flow monitoring and measurement agents, or QoS schedulers deployed in-line within the network or at the edge of such network segments.

6.2 The methodology of developing Open APIs

The methodology towards creating Open APIs is as follows:

1. Understand the technology domain capabilities and APIs in the target technology domains selected by PREDICT-6G. From the existing APIs, PREDICT-6G needs to select which ones may be leveraged for providing data plane programmability in the respective technology domain. APIs may be useable as is; by wrapping them to a stateless transformation interface (e.g., to simply map between different terms having the same semantics); or need to implement stateful logic to build a useful service (such as monitoring capability) from the mosaics that are natively provided by the underlying technology.
2. Create the Open APIs towards the PREDICT-6G' technology specific MDs. This requires close cross-work package collaboration between PREDICT-6G WP2 and WP3, as WP3 defines the demands for programmable capabilities in the technology domains, and WP2 delivers the means for achieving such programmability in WP2. Therefore, it is expected that the definition of the MDP's Open APIs will be an iterative process, which will be influenced initially by WP3's understanding on the AICP methods and mechanisms, as well as by feedback from integration performed in WP4 and in the Open Labs. In summary, MDP Open APIs will be a collection of living APIs organically developing according to the project requirements and cross-WP integration progress, rather than a rigid set of pre-defined APIs derived from an offline planning process.

The Open APIs will be defined according to the Open API specification [31], which will be provided in the sequel to the current deliverable, namely D2.2 (due in M11 of the PREDICT-6G project).

6.3 Basic categories of Open APIs

The Open APIs provided by PREDICT-6G's MDP may be classified into the following categories. This categorization helps understand the types of programmable services that MDP needs to provide towards the AICP, and fosters collaboration between WP3 and WP2 to jointly shape the specification of the APIs according to the mechanisms and closed loops defined in the MDs. For each category, the key capabilities and utility of the APIs are given, which will serve as the starting point towards the process of defining the APIs in more detail.

6.3.1 Time synchronization

It programs and exposes the time sync capabilities of the technology domain (if any):

- Configuration of the clock source(s): means of being synced to a clock source, especially if the clock source is outside of the domain (or exposing the lack of support for external clock sources in domains accepting internal clocks only).
- Exposure of internal clock(s): means of providing clock sync to other domains.
- Resiliency against clock sync attacks: mechanisms such as clock source redundancy (sync to multiple clock sources), backups, auto-renegotiation of clock master/slave relations (within or across domains).

6.3.2 Measurement collection

It programs measurement capabilities and exposes measurements collected from the domain:

- Traffic monitoring for packet, flow and service level measurements (according to the KPIs defined in [1]).
- Service level KPI monitoring.
- Network performance measurements (with configurable aggregation and sampling frequency whenever supported by the domain) and network state monitoring (such as congestion build-up).
- Device location and mobility events (if mobility is supported by the domain).

6.3.3 Service automation

It exposes control points to impact services and network mechanisms within the domain:

- Service provisioning: creation of a new service within the domain according to the domain's service concept (which is specific to the domain's technology)
- Quality of service management mechanisms: exposure of QoS mechanisms and their control parameters, such as scheduler configurations or access to PREOF/PAREO techniques available within the domain.
- Enforcement of service flow separation and service path allocation (if supported by the domain)

6.3.4 Exposure of topology, capability, resources and domain services

It exposes information about the domain's internal topology, supported deterministic capabilities and resources that enables the planning, provisioning, and assuring of existing and new services by the AICP:

- Topology: the topology is exposed at the level of per domain service endpoints with logical connections between pairs or service endpoints that could be used for domain level services.
- Capabilities: exposure of domain level or logical connection level capabilities. E.g., the support of intra-domain U-plane deterministic mechanisms such as PREOF or 802.1 Qbv schedulers, or support for cross-domain U-plane mechanisms such as replication without elimination (i.e., splitting PREOF into replication and elimination and mapping them to different technology domains – a novel innovation by PREDICT-6G).
- Resources: exposure of domain resources and networking parameters along a logical connection, such as available bandwidth, or intrinsic delay (that is a minimum delay supported by the domain between two service endpoints), reliability or availability. The resources may dynamically change as a function of user demand, the existing service flows and their demand, the traffic mix served by the domain (including non-deterministic traffic in addition to deterministic flows), etc.

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- Service: exposure of the domain-level services whose lifecycle is managed by or via the domain controller. Information exposed about each domain level service should include the domain specific service endpoints, the target parameters of the service (QoS, resiliency, reliability, availability, etc.) and the status (such as achieved QoS, whether there is any congestion/overload detected or predicted, etc.). The domain level service information is leveraged by the E2E service composition to ensure that the concatenation of domain level services provides a contiguous E2E service with proper E2E QoS.

6.4 Open APIs for Non-Public Networks

One of the initiatives performed at the 5TONIC lab, in the scope of Smart Factory use case, is to develop a Network Digital Twin of a portion of 3GPP network, corresponding to the Non-Public part of the network described in Section 4.8, which basically contains the data plane of the network, for both Core and Radio Access Network (RAN).

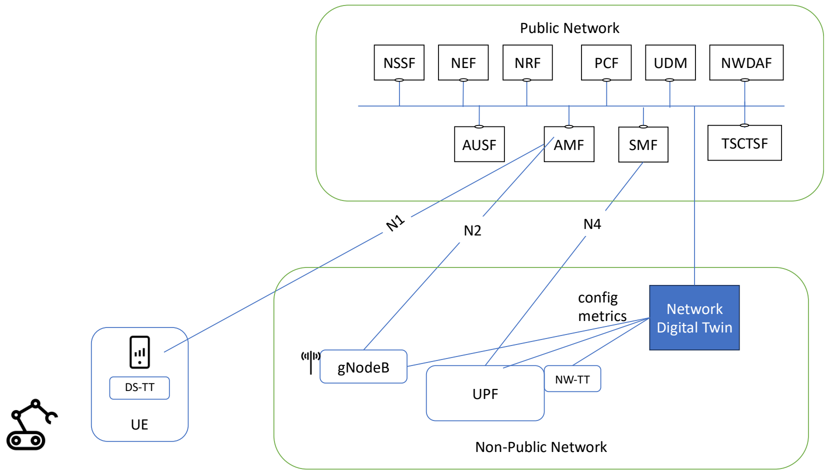

Figure 27 Network Digital Twin for Non-Public Networks (5Tonic)

This approach allows to simplify the management of the data plane in general, including the deterministic features. The Network Digital Twin will expose the Non-Public Network capabilities using the standard functions defined by the 3GPP, mainly the Network Exposure Function.

6.5 Open APIS for network slices in transport with notion of determinism

IETF is the SDO devoted to the development of specifications for the control and management of transport networks. One of the activities in place is the definition of a standard data model for the requesting of network slicing services [32].

The current model defined a network slice in transport as a set of connections with associated Service Level Objectives (SLOs) and Service Level Expectations (SLEs). The SLOs are measurable (e.g., throughput), while the SLEs are not (e.g., isolation).

The set of connections constituting a slice can represent any-to-any, point-to-point, or point-to-multipoint connections. Figure 28 represents the concept of network slice in the model.

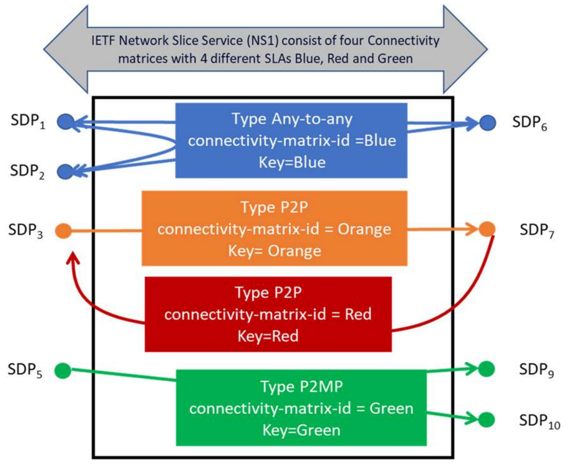

Figure 28 Concept of IETF network slice

The existing model does not incorporate parameters to express the need of determinism, reliability, or predictability. Thus, there is gap that needs to be covered for adapting the network slice in the transport network to the properties.

The objective of this line of work is then the definition and extension of models permitting the programmability of transport network slices including notions of determinism. This implies the extension of existing IETF work on network slicing. As a way of validating the proposed extensions, it is considered to perform a potential PoC in case of having equipment allowing dynamic configuration of deterministic capabilities.

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6.6 Dynamic Scheduler Interface

Related to the dynamic scheduler proposed in 4.3, in Task 2.2 we will focus on the specification of the interfaces that enable the scheduler to communicate with the TSN data plane, and if necessary, with the control plane. To create such an interface, at least the following requirements need to be defined:

- Scheduler Inputs: To make informed scheduling decisions, relevant information regarding UL and DL transmissions should be collected. This information may include as Channel State Information (CSI), Queue State Information (QSI), Packets Information (PI), and targeted QoS (latency, reliability, etc.).
- Scheduler Outputs: Number of UL slots and number of DL slots per frame, RBs allocated to each flow and QoS measurements, in particular, latency statistics over the wireless segment.

7 Roadmap

Table 1: Roadmap of contributions per partner

					Y1		Y2	Y3
					M8	M11	M24	M27
Category of contribution	Task	Partner	Title of contribution	Small description	D2.1	D2.2	D2.3	D2.4
Assess TSN over Wi-Fi	T2.1	CNR/Intel	Evaluation of the synchronization offset for a network with more stations	This extends the first set of experiments performed to assess the possibility of achieving TSN synchronization over a Wi-Fi network		X		
	T2.1	CNR/Intel	Evaluation of latency	Determine the times necessary to execute the various steps involved in the E2E communication, which includes the protocol stacks execution times, queuing latencies, actual data transmission, etc., in such a way to achieve a complete device characterization.		X		
	T2.1	CNR/Intel	Assessment of IEEE 802.1 Qbv for traffic scheduling	Implement time-aware packet scheduling and prioritization, facilitating the coexistence of real-time and best-effort traffic.		X		

	T2.1 T2.2	Intel	Enable and evaluate TSN redundancy and resiliency to interference/attacks and mobility	Take advantage of the TSN redundancy capability (as defined in the IEEE 802.1CB standard) to provide path diversity and eliminate outages or delays due to events like roaming and interference in a mobile scenario. Outputs are experimental/simulation results		X		X
	T2.1 T2.2	Intel	Leverage multi-radio/MLO (Wi-Fi 7 – available in 2024) towards seamless roaming	Evaluate upcoming MLO feature for seamless mobility. Outputs are experimental/simulation results				X
	T2.1	Polito	Deterministic channel access in Wi-Fi	Algorithms for optimal MAC and physical-layer configuration in Wi-Fi, in order to enable deterministic access by nodes based on the requirements of the traffic and applications they need to support. Algorithms will leverage features of Wi-Fi 6 and 7, and ML approaches whenever appropriate. 2023: Identification of features in Wi-Fi 6 and 7 that can be leveraged by algorithms; problem formulation; simulations to build data sets for the development of data-driven approaches. 2024: Algorithms development and implementation in simulation; performance evaluation via simulation; initial integration			x	x

				(in collaboration with WP4). 2025: Full integration and experimental testing.				
	T2.1	UC3M	Scheduling of TSN traffic based on rTWT	Analytical and simulation work	x		x	x
Dynamic re-configuration of TSN-based wired/wireless networks	T2.1	CNR/Intel	Switching of the communication flow from the Wi-Fi link to the Ethernet one (this was not tested in the experiments carried out till now)	In the context of Predict-6G, there is the need of re-configuring the data planes of networks as a consequence of analyses and/or predictions that detect or envisage anomalies, with the goal of ensuring and maintaining E2E bounded latency and reliability. This requires the seamless switching of communication flows among different links, that may be either wired or wireless.		X		

	T2.1 T2.2	CNR/Intel	Assessment of the IEEE 802.1Qbv behavior (this was not tested in the experiments carried out till now)	TSN features have to be maintained when moving a communication flow from one link to another. The objective of this activity is, actually, to address such a challenging scenario and, in particular the behavior of KPIs such as packet loss, latency and jitter that may be, in principle, impacted by the flow switching. The activity will be mainly experimental.		X		
	T2.2	CNR/Intel	Use of different SDN controllers	Evaluate different approaches				X
	T2.1	CNR/Intel	Assessment of the TWT behavior	Assess switching approach when utilizing TWT scheduling				X

Non-deterministic devices and networks	T2.3	Nokia	Flow monitoring for non-deterministic domains	Description: Domains with no deterministic capabilities usually lack the means to obtain measurements relevant to deterministic traffic forwarding (such as packet timing, latency/jitter, loss detection, etc.). These enablers need to be created using user plane nodes attached to the border of such network segments or (if possible) within the domain itself. Tentative yearly plan including implementation: 2023: planning of measurement capabilities (within the MDP) and relevant data collection APIs (provided by MDP to AICP) including the technical means of their implementation. 2024: implementation and validation in the Budapest Open Lab 2025: integration to Nokia use case (critical communication) – may already start in 2024.		X		

	T2.3	Nokia	Traffic management for non-deterministic domains	Description: Domains with no deterministic also lack the means to exercise control over the traffic flowing through them; this may mean the lack of flow admission control, traffic policing, and lack of QoS disciplines at forwarding nodes. Such capabilities need to be partially added (especially admission control to regulate the flows that may traverse the network segment) to enable their integration to a deterministic E2E. Tentative yearly plan including implementation: 2023: planning of traffic management capabilities (within the MDP) and relevant control APIs (provided by MDP to AICP) including the technical means of their implementation. 2024: implementation and validation in the Budapest Open Lab 2025: integration to Nokia use case (critical communication) – may already start in 2024.			X	

	T2.2	Cogninn	Programmable APIs for service automation	Automation is essential to manage sprawling, heterogeneous multi-domain/multivendor network efficiently. Operators therefore increasingly expect and demand support for standards-based programmable interfaces in their NFs, both physical and virtual. If an NF is not programmable via an automated, machine-readable management framework, it likely is not an option for a 5G network. First, the NF must provide a machine- to-machine management interface, not just a human-to-machine interface like CLI. It should expose data in a standardized format, such as YANG. And, it should define a set of standard operations (that is, a protocol), so that it can be configured via third-party controllers and orchestrators. Beyond these basic principles, however, NFs that participate in 5G networks and services must meet several other programmability requirements, including support for transactions, intent-based networking.			x	

	T2.3	Cogninn	Programmable and intelligent management plane in TSN enabled RAN	Potential application to programmable and intelligent management plane in TSN enabled RAN. To this end, we aim to provide programmability and automation through the aforementioned APIs for a cross RAN/Core collaboration. In such a model, high-level orchestrators are not burdened with managing every procedural step for every NF, in every domain, contributing to an E2E service.			x	
Interfaces to AICP	T2.2	Nokia	MDP-AICP interface integration to Nokia Budapest Lab	Description: Technology specific Management Services (part of AICP) need to integrate with the specific devices that are available in a specific deployment. In the Nokia Budapest Lab, the MDP-AICP integration needs to be done withing the existing 5G SA test network and potential additional devices (physical or virtual/emulated). Tentative yearly plan including implementation: 2023: definition of the MDP APIs (co-creation between WP2-WP3) in T2.2 and T3.3-T3.4. 2024: implementation and validation in the Budapest Open Lab			X	

				2025: integration to Nokia use case (critical communication) – may already start in 2024.				
General TSN technologies	T2.1	UC3M	Implementation of XDP based IEEE 802.1Qub bridge	Implementation of a bridge with queuing discipline using XDP and validation of its performance.	x	x	x	x
	T2.1 T2.3	UC3M	Testing of XDP bridge on top of IEEE 802.11 and validate Intel deployment with and without XDP bridge	Based on the above, put it on top of IEEE 802.11 and see if we can provide queue disciplines to the wireless. Compare with qdisc disciplines as defined by Intel.			x	x

	T2.1	TID	Scheduling techniques and queueing models with mixed traffic classes	Analysis and definition of proper scheduling strategies in scenarios with a high component of deterministic traffic in contrast with current situation in operational networks. In principle work considered as analytical and simulation. If possible, implementation in real systems, as well.			x	
	T2.2	TID	Development the concept of slice in IETF for the support of determinism, reliability and predictability (e.g., including DetNet)	Definition and extension of models permitting the programmability of transport network slices including notions of determinism. Extension of existing IETF work on network slicing. Potential PoC in case of having equipment allowing dynamic configuration of deterministic capabilities.		x	x	
	T2.3	TID	Cloudification of TSN reliability functions	The objective is the implementation of ultra-reliable and high available virtual functionality equivalent to IEEE 802.1CB Frame Replication and Elimination for Reliability (FRER) standard (i.e., cloud-friendly FRER implementation). Integration of the cloud technological domain on deterministic PRECIT-6G scenarios.			x	
Integration of MDP	T2.3	UC3M	Implementation of DetNet transport	Implementation of DetNet transport over ONOS controller.		x	x	x

	T2.3	UC3M/ ERC	Integrate DetNET control plane with L2 FRER techs	Integrate DetNet dataplane with FRER control plane.			x	x
	T2.3	UC3M/ ERC	Integrate DetNEt cointrol plane with the 3GPP and Wi-Fi	Integrate DetNet development with the Wi-Fi development.			x	x
	T2.3	ERC	Development of multi-domain reliability	Development of reliability solution for the DetNet data plane.				
3GPP TSN	T2.1	UPC	Design of dynamic scheduling algorithms for mixed traffic	Design of schedulers for mixed traffic: time-sensitive periodic, time-sensitive aperiodic and best-effort. Optimal power, MCS and subcarrier (OFDMA) allocation. Integration with 802.1 TSN (802.1Qbv compatible). Dynamic optimization of the TDD frame structure (DL vs UL time assignment) using Reinforcement Learning methods. Study of admission/congestion mechanisms for coordinated and contention-based access.	x	x	x	x
	T2.1	UPC	Design of multi-cell coordinated scheduling strategies	Coordinated scheduling of users attached to different interfering gNB/APs. Optimal power and subcarrier allocation. Extension to coordinated beamforming.	x		x	x

	T2.1	UPC	System-level simulator for evaluation of scheduling and multi-cell coordination algorithms	3GPP-compliant system level simulator (L1 and L2) for evaluation of scheduling and multi-cell coordination algorithms. Mixed-traffic generation. Wireless channel simulation for industrial scenarios.			x	x
	T2.2	UPC	Dynamic Scheduler Interface	Specification of the interfaces that enable the control plane-based configuration of the TSN data plane.			x	x
	T2.1	IDE	Linking Shared PDU Sessions and PDU sets with E2E DetNet Data Plane	Rel.18 saw the introduction of shared PDU sessions and PDU session sets for a better handling of different QoS service flows for a single service. The approach is to implement the new PDU session handling in the LAS demo with TSN-enabled switching capabilities in the UE and UPF and allow the integration with E2E MFs towards a multi-domain Data Plane Timeline: Design planned in 2023, implementation in 2024.	x	x	x	x

	T2.2	IDE	Enable programmable 3GPP User Plane with Shared PDU Sessions and PDU Sets	It is foreseen to design and implement Domain MFs supporting the exposure and control of relevant data of the T2.1 UP implementation around shared PDU sessions and PDU session sets over TSN-enabled Ethernet PDU sessions.	x	x	x	x
	T2.1	ERC	Development of needed extensions for operation of 5GS as TSN bridge. Time-based schedulers on 3GPP networks	Development of DS-TT, NW-TT and required support ant transport layer	x	x	x	x

8 Conclusions

In this deliverable we describe PREDICT-6G ongoing work and the plans for enhancing the determinism in the multi-domain and multi-technology, which is an ambitious objective. We propose an architecture that allows to ensure the determinism across different technologies and domains.

We describe how the project organize the **L2 enhancements** in different domains with the purpose of boosting the collaboration across the project partners. We also include preliminary results, that has been published in scientific papers, that demonstrate the enhancements in the determinism introduced by our innovations. These works are important as they are confirming that our approach might produce important results and give to us first-hand information of the behavior of new L2 mechanism in the wireless domain. It is worth to mention that we also contribute to standards, and we already started the work for designing the Proof-of-Concepts expected for this project.

In addition to the L2 enhancements, we define the way of **integrating** different domains with different technologies, which is key for supporting the definition of an E2E deterministic services. Also, we include in this deliverable how the MDP is going to **expose** the determinism towards the control plane.

In summary, we are presenting a good advance of the project at the time of delivering this document, as well as the foundations of the future developments of the project, which are included in the **roamap.**

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