Experimental Evaluation of a Multi-Domain TSN Scenario in Industry 4.0

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Abstract

The advent of 5G deployments and the anticipation of 6G have initiated a concerted effort to define new network and application services that leverage these technologies. A key focus of this effort is deterministic networking, which provides the reliability, time sensitivity, and predictability essential for supporting critical services and applications. This article presents a solution to support multi-domain deterministic communications, integrating various technology-specific deterministic networking solutions—namely IEEE 802.11, IEEE 802.1 TSN, and 3GPP 5G domains—over an IETF DetNet data plane. Our goal is to create a realistic infrastructure for developing the next generation of deterministic services. Key contributions include the design, deployment, and performance characterization of the multi-domain data plane, as well as its integration into a real-life use case such as the remote control of a robotic dog.

CCS Concepts

• **Networks → Network experimentation**; *Bridges and switches*; *Mobile networks*; **Transport protocols**; *Programmable networks.*

Keywords

DetNet, TSN, multi-domain, 3GPP, TSN-enhancements, Industry 4.0

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1 Introduction

Significant efforts are underway to develop new network and application services that leverage 5G technology and the forthcoming 6G. A primary focus of these efforts is the creation of networks with deterministic features. A deterministic network is characterized by its reliability, time sensitivity, and predictability, which are essential for critical services that require guarantees on delay, jitter, and packet loss.

The importance of developing deterministic networks has been emphasized by various standardization bodies in recent years. Examples include IEEE 802.1 Time-Sensitive Networking (TSN), which deals with time-sensitive communications at the bridge level (mainly for Ethernet), and discussions on determinism in IEEE 802.11be (WiFi 7) and IEEE 802.11bn (the upcoming WiFi 8, also called ultra-reliable communications), as well as the 3GPP's definition of the Time Sensitive Communication (TSC) subsystem.

Determinism is becoming more important in modern network design. However, to make deterministic services widely available in the future, and expand its use outside a single technological domain, we need to connect different technologies. The IETF's Deterministic Networking (DetNet) group is working on creating a Layer 3, Internet-wide, multi-domain deterministic network.

This article aims to deploy and evaluate a multi-domain deterministic experimental platform. It uses a DetNet-based data plane that integrates IEEE 802.11, IEEE 802.1 TSN, and 3GPP domains, providing researchers with a realistic network infrastructure to develop the next generation of deterministic services.

As use case, we propose the remote control of a TSN-critical application, specifically a robotic dog, which requires both low latency and low jitter. This is accomplished through enhancements in the involved domains. The WiFi and wired domains utilize 802.1Qbv, a gate-based mechanism, to ensure TSN traffic resources by synchronizing the clocks of these domains using distributed 802.1as, over the air in the case of WiFi. We enhance the OAI 3GPP domain by implementing three mechanisms to achieve determinism: traffic

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throttling, modifications to the MCS selection algorithm, and dejittering through frame reservation for TSN traffic. Our main contributions to the research community include:

- Designing and characterizing TSN domains for wired 802.1 networks, 3GPP, and 802.11 WiFi. This involves detailed performance analysis and optimization to enhance deterministic traffic handling in these diverse network environments.
- Implementing a common data plane using DetNet technology. This data plane facilitates seamless multi-domain operations, integrating the various TSN domains into a cohesive and interoperable network structure.
- Validating the entire setup with real TSN applications. This validation involves rigorous testing and evaluation to demonstrate the practical utility and effectiveness of the proposed multi-domain deterministic network in handling real-world time-sensitive applications, as the remote control of a robotic dog.

The paper is structured as follows: Section 2 reviews existing solutions for achieving determinism across various domains in Layer 2 (L2). Section 3 introduces our Layer 3 (L3) deterministic solution, DetNet as a data plane to enable multi-domain time sensitivity. Section 4 details the different domains and techniques proposed in our use case. Section 5 describes the characteristics of traffic in a multi-domain TSN network. Last, Section 6 presents the results from our multi-domain use case and Section 7 elaborates the conclusions.

2 L2 Determinism in 3GPP, TSN & WiFi

The integration of deterministic communication across various network technologies is crucial for meeting the demands of modern applications, and a thorough understanding of the different deterministic capabilities of each domain is needed to achieve it. This section explores the state-of-the-art determinism in three key areas: WiFi, Ethernet TSN, and the 3GPP. Each subsection highlights the advancements and standards that enable these technologies to support reliable, latency-constraint services.

2.1 WiFi

Recent developments in WiFi technology are focusing on integrating TSN to improve deterministic communication. The IEEE 802.11 standards, typically linked with WiFi, are advancing to support time-sensitive applications by providing low latency and high reliability. WiFi 6 (802.11ax) and the upcoming WiFi 7 (802.11be) introduce features such as OFDMA and multi-user MIMO, enhancing network efficiency and minimizing latency. Current initiatives aim to combine TSN with WiFi, enabling deterministic services on wireless networks and ensuring that time-sensitive data is delivered within precise time limits [12].

2.2 TSN

IEEE 802.1 TSN is a set of IEEE standards designed to provide deterministic and time-sensitive communication over Ethernet networks. TSN achieves determinism by implementing features such as time synchronization, traffic scheduling, and resource reservation. These features are critical for applications that require guaranteed delivery times and low jitter. TSN is widely being adopted in industrial automation, automotive, and other real-time systems where predictability and reliability are paramount. For example, TSN's time-aware shaper (TAS) ensures that critical data streams are prioritized and transmitted within defined time windows, making it suitable for applications like robotic control systems and automotive networks [8].

2.3 3GPP

The 3rd Generation Partnership Project (3GPP) has advanced deterministic networking in its standards, especially with 5G. 3GPP Release 16 introduced support for TSN, enabling 5G to meet the strict demands of industrial automation, smart grids, and time-sensitive applications like remote surgery and autonomous driving through ultra-reliable low-latency communication (URLLC) [2, 6].

By integrating TSN, 5G networks can provide deterministic communication with guaranteed latency, allowing interoperability with existing TSN networks and ensuring end-to-end deterministic services across diverse networks. This is achieved through 5G system time synchronization with TSN time domains and 5G QoS mechanisms [3, 7].

3GPP's work on deterministic networking continues into future 6G standards, aiming for even lower latency and higher reliability for applications like tactile internet and immersive virtual reality [5, 13]. Multi-domain services require a common dataplane to integrate these tools. This is accomplished using a DetNet, as explained in the following section.

3 Detnet-Based L3 Multidomain Dataplane

To integrate various technological domains into a unified end-to-end deterministic data plane, recent advancements from the IETF DetNet working group are utilized. DetNet establishes deterministic data paths over Layer-2 bridged and Layer-3 routed segments, ensuring bounds on packet reordering, latency, loss, and jitter for high reliability. The DetNet data plane architecture is split into two sub-layers: the service sub-layer, which handles service protection and packet reordering, and the forwarding sub-layer, which provides congestion protection and traffic engineering for low loss, assured latency, and minimized out-of-order delivery.

End-systems in a DetNet domain encapsulate packets based on their service needs, with edge DetNet nodes operating in both sub-layers to deliver these functionalities.

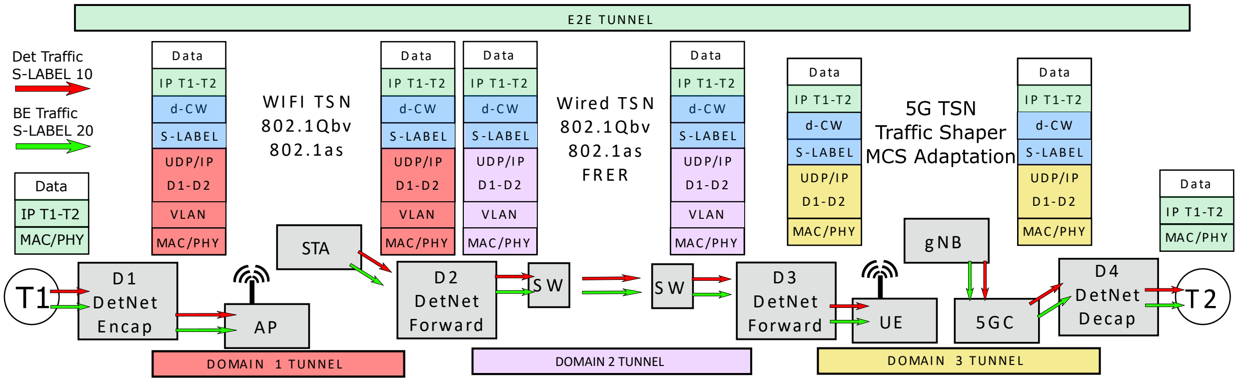

Figure 1: Detnet dataplane architecture proposal with in detail packet composition.

Transit DetNet nodes offer the required QoS for traffic flows without necessarily being aware of the DetNet service layer. In addition, the architecture proposes a control and management plane to configure the data plane and provide per-flow QoS, along with operations, administration, and management (OAM) mechanisms to keep deterministic properties.

Different RFCs are specified by IETF to use as DetNet data planes. We have adopted the MPLS over UDP/IP solution [11], as it allows for the complete implementation of the forwarding and service sub-layer functionalities of the DetNet data plane. MPLS over UDP/IP is particularly advantageous versus other data plane options such as MPLS only [10], because it combines the scalability and routing capabilities of IP networks with the traffic engineering benefits of MPLS.

Our development of DetNet routers utilized eBPF and XDP technologies to bypass the kernel and process packets swiftly, deterministically, and directly from the user plane. This approach enables fast and consistent handling of traffic, enabling the deterministic capabilities of the network.

In this implementation, we propose as well extending DetNet router capabilities to function as translators between different technological domains. This extension will enable each domain that follows a DetNet node to recognize and appropriately manage the data flows, ensuring that Time-Sensitive Networking functionalities are correctly applied. In practice, this means that DetNet routers will be aware of the specific requirements of the subsequent domain and will adjust flow identification information—mapping it into VLANs, Type of Service (ToS), or other fields—accordingly. This approach aligns with concepts similar to the Domain-Specific Translation Terminals (DSTT) at User Equipment (UE) and Network-Wide Translation Terminals (NWTT) at User Plane Function (UPF), facilitating seamless and efficient flow management across diverse network environments.

Even though DetNet's Packet Replication, Elimination, and Ordering Functions (PREOF) are not required in this specific scenario, they can be configured on demand by updating the forwarding sub-layer configuration to activate these features. By leveraging PREOF, the network's reliability can be enhanced while still maintaining deterministic performance.

Our DetNet-enabled multi-domain testbed is depicted in Figure 1, featuring two endpoints (T1 and T2) connected through two DetNet edge routers (D1 and D4). The proposed scenario spans three distinct technological domains: an experimental WiFi TSN setup with one AP and one STA, a commercial TSN wired domain consisting of four switches and a 5G network based on OAI. The figure also illustrates the protocol stacks and tunnels utilized in the experiments.

Next, we detail how we extended each of the single domain capabilities to support multi-domain deterministic communications by leveraging the IETF DetNet data plane. This extension integrates wired TSN, enhanced WiFi TSN, and an open-source-based 5G RAN and core.

4 Technological Domains

This section enumerates the domains constituting the E2E multi-domain network and details the capabilities inherent to each, as depicted in Figure 2. Particular emphasis is placed on the advancements within the 3GPP framework to support for TSN, highlighting the integration and enhancements achieved across diverse technological domains to enable latency and jitter bounded, time synced and packet loss free transmissions E2E.

4.1 WLAN

The WLAN domain leverages IEEE 802.1 TSN capabilities to enable time synchronization and deterministic latency over wireless links. These capabilities include the IEEE 802.1AS Generalized Precision Time Protocol (gPTP) for time synchronization and IEEE 802.1Qbv time-aware scheduling to create protected windows for time-critical traffic – see 2-left. This ensures precise control over latency and minimizes

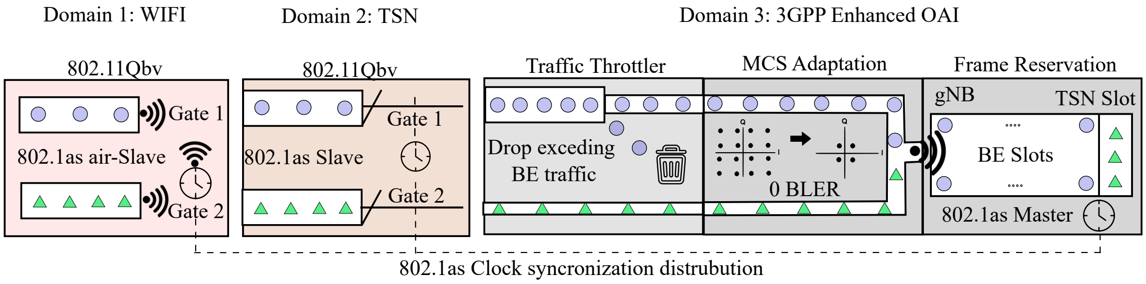

Figure 2: Different features implemented to achieve determinism in multi-domain networks

interference from non-critical traffic. The WLAN TSN implementation in our multi-domain is based on Intel's development, utilizing NUCs with AX210 WiFi 6/6E chipsets [9].

4.2 Ethernet TSN

The Ethernet TSN domain uses switching technologies to provide deterministic networking over wired links. Key capabilities include IEEE 802.1Qbv for scheduled traffic and Frame Replication and Elimination for Reliability (FRER) to enhance network robustness – see 2-middle. These technologies ensure high reliability and low latency, making them suitable for critical applications in various industries. Our Ethernet TSN domain makes use of commercial devices.

4.3 3GPP

We deployed a 5G Standalone (SA) network using OpenAirInterface (OAI) to advance the capabilities of next-generation wireless communication systems, implementing mechanisms to enhance the reliability and determinism of the network – see Figure 2-right:

Adaptive Traffic Throttler: We developed an adaptive traffic throttler to limit the total traffic entering the network. This mechanism prioritizes TSN traffic and buffers other traffic when there is insufficient throughput, ensuring that TSN traffic receives the necessary bandwidth.

MCS Selection Adaptation: To guarantee zero packet loss for TSN traffic, we adapted the Modulation and Coding Scheme (MCS) selection. This adaptation dynamically reduces the MCS when necessary to maintain the reliability of TSN communication and reduce the latency and jitter as no retransmissions are done through the wireless channel.

Frame Resource Allocation: We implemented a resource allocation strategy specifically for TSN traffic over the radio frame. This minimizes jitter for periodic TSN traffic, ensuring that time-sensitive data is transmitted with the consistency required for critical applications.

Table 1: Performance of different Modulation Coding Schemes

MCS	3 (QPSK)	9 (4QAM)	12 (4QAM)	16 (16QAM)
BLER	0.00	0.05	0.08	0.2
THR	5 Mbps	10 Mbps	20 Mbps	30 Mbps
LAT nSCHE	3.7-20 ms	3.8-27ms	3.7-26.2ms	3.1-55ms
LAT SCHE	7.3-9.8 ms	6.6-12ms	6.4-11.7ms	7.2-22ms

OpenAirInterface scheduling algorithm allocates resources in the radio frame using RoundRobin techniques, however if packets are released into the network periodically and synchronized with the radio frame, we can force them to always allocate the same subframe. Thus, we experience reduced jitter for all the TSN packets – see Figure 5.

By deploying these mechanisms within our 5G SA OpenAirInterface network, we aim to provide a highly reliable and deterministic network environment, paving the way for innovative applications that demand stringent performance.

Table 1 shows the performance of our system using different combinations of the presented mechanisms. Results show that BLER conditions the latency of the system, as HARQ increase the latency and jitter, due to packet retransmissions. In addition, MCS conditions the channel capacity and thus, the dynamic traffic throttler threshold, as it is adapted to let TSN + max BE traffic go through the link.

In addition, depending on the latency and jitter requirements, our system chooses a configuration, scheduling TSN traffic within the frame in case it is necessary and achieving latencies from 7.3 to 9.8 ms in the best scenarios.

5 Real life TSN Traffic Models & Use Cases

While Best Effort (BE) traffic is typically generated as burst type, random size and aperiodic, TSN traffic exhibits several key characteristics that are crucial for its applications in various industries. Periodicity is a fundamental attribute, where TSN traffic consists of periodic data streams with fixed intervals between packets. This ensures predictable data transmission, essential for real-time applications. For instance, in industrial automation and automotive networks, precise timing is critical, and periodic traffic helps coordinate activities effectively [4, 12].

Packet size in TSN networks can vary but is generally optimized to fit within the network's maximum transmission

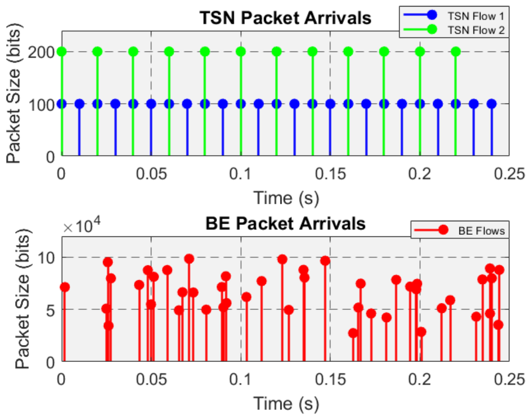

Figure 3: Distribution of packets over the time of our TSN Traffic Model vs BE Traffic Model

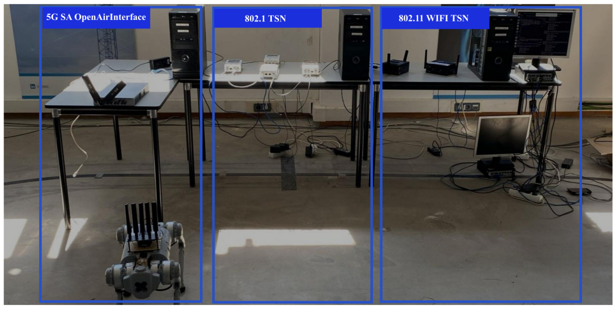

Figure 4: Multi-domain scenario setup

unit (MTU) to minimize fragmentation and ensure efficient transmission. Smaller packet sizes are preferred in industry to reduce latency and improve predictability.

Latency is another critical aspect, with TSN aiming to provide low and bounded latency through mechanisms such as time-aware scheduling. This is vital for applications requiring immediate response times [1, 14].

Jitter, or the variability in packet arrival times, is minimized in TSN to maintain determinism, ensuring consistent and predictable data delivery. High reliability is achieved through redundant paths and fault-tolerant protocols, ensuring data delivery even during network failures.

Additionally, TSN supports multiple traffic classes with different priority levels, allowing coexistence of critical control messages and less time-sensitive data. Central to TSN's functionality is synchronization, achieved through protocols like IEEE 802.1AS, which ensures all network devices share time reference for coordinating periodic data streams [2].

Our use case involves a robot dog connected through a multi-domain scenario network, with a WLAN network interfacing via wired connectivity to a 5G Core and network. The remote user controls the robot dog using a digital twin (DT) to streamline operation at a remote production plant deployment. The DT provides a real-time virtual representation of the robot dog, allowing for precise monitoring and control of its actions. Communication between the DT application and the actual robot dog involves commands traveling through the WLAN network, transitioning through the wired network, and reaching the robot dog via another 5G network at the deployment site. This configuration must ensure low-latency, reliable, and real-time control, essential for the operation of the robot dog in an industrial setting.

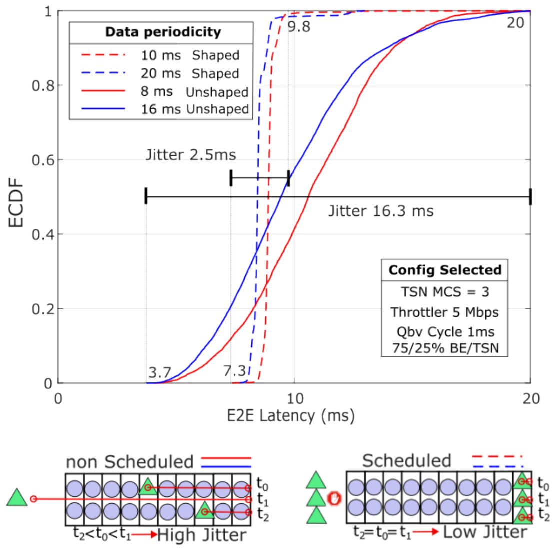

Figure 5: Latency distribution per packet for different traffic loads

For this use case, we employed a Unitree Go1 robot dog. We captured the traffic of both the main control loop and the status report of the robot's odometry, which are crucial for the DT. These two data streams form the TSN traffic flows we aim to ensure. We generated two traffic models, as shown in Figure 3 representing these TSN traffic classes: the control loop consists of a 100-byte packet every 10ms, and the odometry data comprises a 1k-byte packet every 20ms. Additionally, we generated BE traffic in the background using a random exponential Poisson arrival model to simulate real-life BE background traffic as accurately as possible.

6 E2E Measurements

Next, we conduct an experimental analysis of our DetNet multi-domain implementation. We adopt, as illustrative use case of multi-domain deterministic communications, the use of a Digital Twin (DT) to remotely control a robot dog. The DT of the robot dog provides a real-time virtual representation, enabling precise monitoring and control over its actions.

Commands from the DT pass through a WiFi network, transition into a wired network, and finally reach the robot dog via 5G, as shown in Figure 4. The critical, time-sensitive traffic carrying these commands reflects real TSN characteristics, with the robot's control loop sending one 0.1 KB packet every 10 ms. Though this packet size is slightly larger than typical TSN traffic, it suits the use case.

To meet service requirements, the network domains are configured as follows: WiFi and wired deterministic 802.1Qbv implementations have a 1 ms cycle, with 25% dedicated to deterministic traffic. The 3GPP domain uses MCS 3 to minimize latency and jitter, ensuring a 0 Block Error Rate (BLER) on the radio link. Additionally, dynamic input throttling is configured for Best Effort (BE) traffic.

We conducted our experiments with varying the periodicity of the TSN traffic with random background Best Effort (BE) traffic. Figure 5 shows the latency achieved for both non scheduled TSN packets generated every 8 ms (red) and 16 ms (blue) and scheduled TSN packets, same traffic than before but shaped every 10 ms (red discontinuous) for the first and shaped to 20 ms the latter (blue dis continuous). As the figure shows, when the packets are not scheduled in the same subframe (Figure 5 - bottom left), jitter increases due to processing variation. Opposite, when the packets are scheduled in the same subframe (Figure 5 - bottom right), the jitter is reduced as the processing time does not vary per packet. Latencies introduced by both WiFi and Ethernet are negligible compared to 3GPP.

7 Conclusions

This study successfully demonstrates the implementation and validation of a multi-domain deterministic communication scenario, critical for modern industrial applications. By integrating DetNet across various domains, including IEEE 802.11, IEEE 802.1 TSN, and 3GPP 5G, the research addresses the challenges associated with ensuring predictable service delivery in diverse network conditions.

The developed solutions, which include enhancements to an open-source 5G platform, have shown significant improvements in reducing retransmissions, decreasing jitter, and enhancing overall reliability. These improvements are crucial for applications requiring stringent performance guarantees, such as industrial automation and remote robotic control.

A key contribution of this work is the design and characterization of a data plane that integrates multi-domain technologies to enhance determinism. The study not only demonstrates the feasibility of these integrations but also highlights the need for further advancements in deterministic behavior within 3GPP to mitigate interference.

Moreover, the successful deployment of these mechanisms in a real-world use case, involving the remote control of a robotic dog, underscores the practical applicability and effectiveness of the proposed multi-domain deterministic network. The experimental results validate the setup, showing that the integrated network can handle real-time, time-sensitive applications effectively.

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