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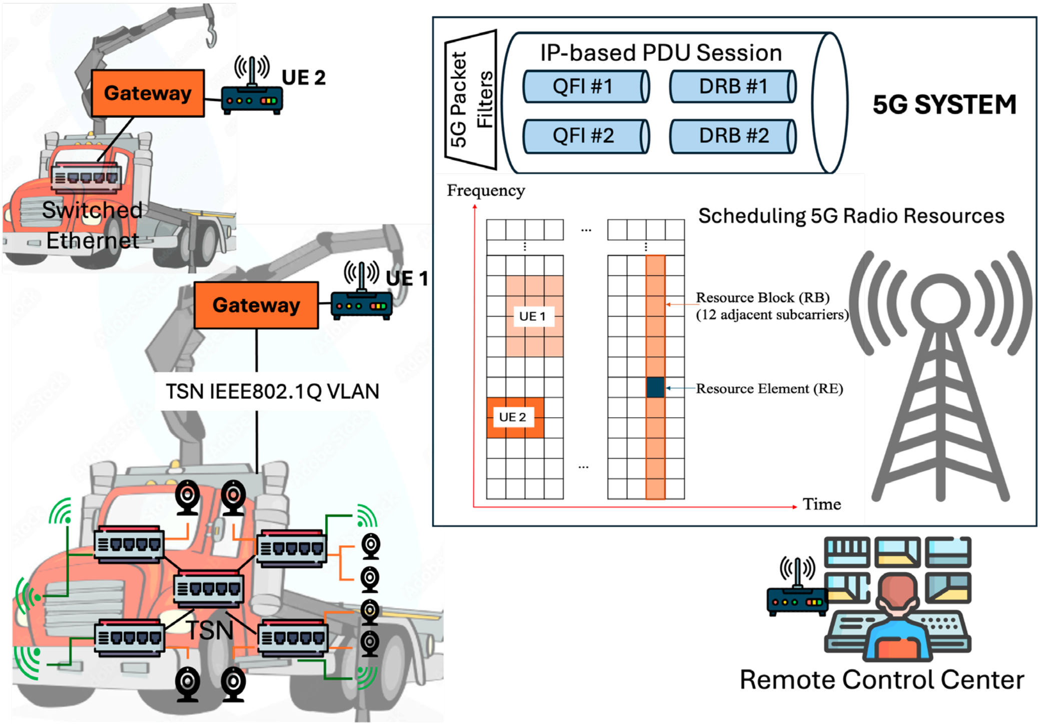
# Real-time Communication in Integrated TSN-5G Networks

**Zenepe Satka**



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# REAL-TIME COMMUNICATION IN INTEGRATED TSN-5G NETWORKS

**Zenepe Satka**

**2025**

School of Innovation, Design and Engineering

ISBN 978-91-7485-705-4
ISSN 1651-4238
Printed by E-Print AB, Stockholm, Sweden

Mälardalen University Press Dissertations
No. 430

# REAL-TIME COMMUNICATION IN INTEGRATED TSN-5G NETWORKS

Zenepe Satka

Akademisk avhandling

som för avläggande av teknologie doktorsexamen i datavetenskap vid Akademin för innovation, design och teknik kommer att offentligen försvaras måndagen den 12 maj 2025, 09.15 i Gamma (och via Zoom), Mälardalens universitet, Västerås.

Fakultetsopponent: Professor Jean-Luc Scharbarg, University of Toulouse, France

Akademin för innovation, design och teknik

# Abstract

The rising demand for real-time applications with ultra-low end-to-end network latency has driven advancements in communication technologies. The IEEE 802.1 Time-Sensitive Networking (TSN) is a set of standards that enable low-latency wired communication, meeting the stringent timing requirements of real-time applications. TSN uses wired communication and lacks the mobility of wireless networks. To overcome this limitation and broaden the applicability of TSN across diverse use cases, the integration of TSN with wireless technologies is essential. The fifth generation of cellular networks (5G) supports real-time applications by providing reliable communication with latencies as low as 1~ms. Seamless integration of TSN and 5G is needed to fully utilize the potential of these technologies in many contemporary and future industrial applications. However, achieving this integration presents significant challenges due to the fundamental differences between TSN and 5G, particularly in ensuring the applications requirements on end-to-end Quality of Services (QoS).

This thesis addresses the challenges of integrated TSN-5G networks, focusing on ensuring end-to-end QoS, traffic forwarding, and real-time scheduling. It presents a systematic literature survey of the existing research on TSN-5G integration that identifies gaps in the current research, including the need of a dedicated TSN-5G gateway to ensure seamless integration. To bridge this gap, the thesis proposes novel techniques to ensure end-to-end QoS and traffic forwarding, validated through a proof-of-concept implementation in a private 5G setup. Moreover, the thesis tackles the challenge of scheduling 5G radio resources for real-time TSN flows with diverse timing requirements. It introduces flow-based radio resource scheduling approaches that adapt to dynamic channel conditions and ensure latency guarantees for the transmission of TSN flows over 5G. These contributions enable real-time communication in integrated TSN-5G networks, paving the way for advanced real-time applications across various industrial domains.

ISBN 978-91-7485-705-4
ISSN 1651-4238

*“To the resilient souls who refuse to surrender, the sleepless nights and hardships that forge strength, and the mentors who illuminate the path - growth is born in perseverance.”*
*– Z*

# Abstract

The rising demand for real-time applications with low end-to-end network latency has driven advancements in communication technologies. Time-Sensitive Networking (TSN) is a set of standards that enable low-latency wired communication, meeting the timing requirements of real-time applications. However, TSN lacks the mobility of wireless networks, hence it is essential to integrate TSN with wireless technologies. The fifth generation of cellular networks (5G) is capable of supporting the timing requirements of real-time applications. There is an urgent need for seamless integration of TSN and 5G to fully utilize the combined potential of both technologies. However, achieving this integration presents significant challenges due to the fundamental differences between these two technologies. This thesis addresses the challenges of integrating TSN-5G networks, focusing on ensuring end-to-end QoS, traffic forwarding, and real-time scheduling. It presents a systematic literature survey of the existing research on TSN-5G integration, identifying gaps in the current research, including the need of a dedicated TSN-5G gateway to ensure seamless integration. To bridge this gap, this thesis proposes novel techniques to ensure end-to-end QoS and traffic forwarding, validated through a proof-of-concept implementation in a private 5G setup. Moreover, the thesis tackles the challenge of scheduling 5G radio resources for real-time TSN flows with diverse timing requirements. It introduces flow-based radio resource scheduling approaches that adapt to dynamic channel conditions and ensure latency guarantees for the transmission of TSN flows over 5G. These contributions enable real-time communication in integrated TSN-5G networks, paving the way for advanced real-time applications across various industrial domains.

# Sammanfattning

Den ökande efterfrågan på realtidsapplikationer med låg end-to-end nätverkslatens har drivit framsteg inom kommunikationsteknik. Time-Sensitive Networking (TSN) är en uppsättning standarder som möjliggör trådbunden kommunikation med låg latens och uppfyller tidskraven för realtidsapplikationer. TSN saknar dock mobiliteten hos trådlösa nätverk, därför är det viktigt att integrera TSN med trådlös teknik. Den femte generationen av cellulära nätverk (5G) kan stödja tidskraven för realtidsapplikationer. Det finns ett akut behov av sömlös integration av TSN och 5G för att fullt ut utnyttja den kombinerade potentialen hos dessa teknologier. Men att uppnå denna integration innebär betydande utmaningar på grund av de grundläggande skillnaderna mellan dessa två tekniker.

Denna avhandling tar upp utmaningarna med att integrera TSN-5G-nätverk, med fokus på att säkerställa end-to-end QoS, trafikvidarebefordran och realtidsschemaläggning. Den presenterar en systematisk litteraturundersökning av befintlig forskning om TSN-5G-integration, som identifierar luckor i den aktuella forskningen, inklusive behovet av en dedikerad TSN-5G-gateway för att säkerställa sömlös integration. För att överbrygga detta gap, föreslår avhandlingen nya tekniker för att säkerställa end-to-end QoS och trafikvidarebefordran, validerade genom en proof-of-concept-implementering i en privat 5G-installation. Dessutom tar avhandlingen sig an utmaningen att schemalägga 5G-radioresurser för realtids-TSN-flöden med olika tidskrav. Den introducerar flödesbaserade radioresursschemaläggningsmetoder som anpassar sig till dynamiska kanalförhållanden och säkerställer latensgarantier för överföring av TSN-flöden över 5G. Dessa bidrag möjliggör realtidskommunikation i integr-

erade TSN-5G-nätverk, vilket banar väg för avancerade realtidsapplikationer över olika industriella områden.

# Acknowledgment

First and foremost, I would like to express my gratitude to the exceptional team of supervisors: Saad Mubeen, Mohammad Ashjaei, Masoud Daneshtalab, Hossein Fotouhi and Mikael Sjödin, who demonstrated that only collaboration and tolerance can foster a truly successful team. Thank you all for bringing the weight of your considerable experience and knowledge to the project.

I would like to express a deep sense of gratitude to my main supervisor, Saad Mubeen, whose unwavering support, guidance, and belief in me have been invaluable from the very first day. Through every success and setback, you have been a steady source of encouragement and inspiration. You're truly a role model, and I am profoundly grateful for all the time and energy you have invested in me, and for the lasting impact you've had on both my personal and academic growth. I am deeply grateful for every moment of our discussions, trips, and meetings. In each of these experiences, I found myself learning from your wisdom, striving to follow the example you set. It is truly a blessing to have had the privilege of your guidance. Thank you for everything.

In addition, I could not have reached this point without the exceptional mentorship of my second supervisor, Mohammad Ashjaei. I am forever grateful for your trust and commitment. You are one of those rare individuals that people wish to have in their lives. Your positive energy and sense of humor, regardless of the circumstances, have served as a guiding light, offering encouragement and strength when needed most. I am deeply thankful for everything you've done to help me succeed.

I am also deeply indebted to Alessandro Biondi for our collaboration and for providing me the possibility to visit the Real-Time Systems Laboratory

(ReTiS Lab) in Pisa, Italy. This visit inspired many ideas that have contributed to the realization of this thesis. I would also like to acknowledge Daniel Casini and Federico Aromolo for all the discussions and support during our joint work.

Next, I take the opportunity to express my sincere gratitude to our industrial partners from Arcticus Systems, Kurt and John Lundbäck, and from HIAB, Hans Lyngbäck and Najeem Lawal. Your expertise, resources, and support have played a crucial role in our success. Moreover, I would like to thank the Ericsson Research Foundation for providing the necessary support for my research visit in Pisa, Italy.

I would like to acknowledge my friends and colleagues at MDU for their constant support, encouragement, and collaboration throughout my journey. Their insights, and shared experiences have greatly enriched this journey. Special thanks to all the professors who provided many courses that enriched my learning experience. I am also deeply grateful to the head of the division, Svetlana Girs, for creating a positive and welcoming work environment from the very first day at MDU.

In addition, I am profoundly grateful to my family, my parents and brother, whose boundless love and support have been the foundation of my journey. Without your dedication and colossal efforts, I would not be where I am today. Last but not least, I am eternally grateful to my beloved husband, who has witnessed the most challenging moments of this journey and, despite them all, he remained steadfast by my side. Your presence, filled with love and encouragement, has been a source of strength, and for that, I am eternally thankful.

This work is supported by the Swedish Governmental Agency for Innovation Systems (VINNOVA) via the PROVIDENT project (grant nr. 2019-05885).

Zenepe Satka,
Västerås, April 2025

# List of Publications

## Papers included in this thesis[1]

**Paper A:** Zenepe Satka, Mohammad Ashjaei, Hossein Fotouhi, Masoud Daneshtalab, Mikael Sjödin, Saad Mubeen. *A Comprehensive Systematic Review of Integration of Time Sensitive Networking and 5G Communication.* Journal of Systems Architecture (JSA), vol. 138, 2023.

**Paper B:** Zenepe Satka, David Pantzar, Alexander Magnusson, Mohammad Ashjaei, Hossein Fotouhi, Masoud Daneshtalab, Mikael Sjödin, Saad Mubeen. *Developing a Translation Technique for Converged TSN-5G Communication.* In the proceedings of the 18th IEEE International Conference on Factory Communication Systems (WFCS), 2022.

**Paper C:** Zenepe Satka, Mohammad Ashjaei, Didrik Nordin, Daniel Ragnarsson, Saad Mubeen. *Enhancing Real-Time Networked Embedded Systems with End-to-end TSN-5G Network.* In the proceedings of the 14th International Symposium on Industrial Embedded Systems (SIES), 2024.

**Paper D:** Zenepe Satka, Mohammad Ashjaei, Hossein Fotouhi, Masoud Daneshtalab, Mikael Sjödin, Saad Mubeen. *QoS-MAN: A Novel QoS Mapping Algorithm for TSN-5G Flows.* In the proceedings of the 28th IEEE International Conference on Embedded and Real-Time Computing Systems and Applications (RTCSA), 2022.

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[1] The included papers have been reformatted to comply with the thesis layout.

**Paper E:** Zenepe Satka, Federico Aromolo, Mohammad Ashjaei, Alessandro Biondi, Daniel Casini, Hossein Fotouhi, Niccolo Borgioli, Masoud Daneshtalab, Mikael Sjödin, Saad Mubeen. *Real-time Scheduling of 5G Radio Resources to Support Time Sensitive Networking Traffic.* MRTC technical report, ISRN MDH-MRTC-355/2025-1-SE, Mälardalen University, 2025.

## Related publications, not included in this thesis

Zenepe Satka, Mohammad Ashjaei, Josefina Nord, William Rosales Mayta, Didrik Nordin, Daniel Ragnarsson, Saad Mubeen. *Bridging TSN and 5G Networks for Real-Time Embedded Systems.* Journal of Systems Architecture (JSA). Under Review.

Zenepe Satka, Deepa Barhia, Sobia Saud, Saad Mubeen, Mohammad Ashjaei. *Experimental Analysis of Wireless TSN Networks for Real-time Applications.* In the proceedings of the 28th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), 2023.

Zenepe Satka, Saad Mubeen, Mohammad Ashjaei, John Lundbäck. *Towards Modelling 5G Communication in Software Architectures of Vehicular CPS.* In the proceedings of the Euromicro Conference Series on Software Engineering and Advanced Applications (SEAA), 2023.

Zenepe Satka, Ines Álvarez, Mohammad Ashjaei, Saad Mubeen. *Work in Progress: A Centralized Configuration Model for TSN-5G Networks.* In the proceedings of the IEEE 27th International Conference on Emerging Technologies and Factory Automation (ETFA), 2022.

# Glossary

**end-to-end QoS** Refers to the ability of a system to support the end-to-end transmission of traffic flows with consistent QoS-es across multiple interconnected and diverse network technologies such as wired TSN and cellular 5G.

**end-to-end** Refers to a data transmission process that involves a series of network components and protocols to deliver the data from the source to the destination.

**flow** Refers to a sequence of packets sent from a common source to a common destination characterized from the same QoS-es.

**interoperability** Is the ability of different networks or systems to communicate easily without the need for additional tools or interfaces.

**real-time** Refers to applications that have strict time constraints or deadlines which has to be met in order for the system to function correctly.

**reliability** Is a key performance attribute in real-time systems often expressed in terms of the probability that a system delivers its expected results without a failure, for a given period of time.

**user equipment** Refers to end-user devices or end stations that are used to access a wireless network, such as 5G.

# Acronyms

**3GPP** 3rd Generation Partnership Project.

**5G** Fifth Generation of Mobile Networks.

**5QI** 5G QoS Indicator.

**AF** Application Function.

**AVB** Audio-Video Bridging.

**BE** Best Effort.

**CBS** Credit-based Shaper.

**CNC** Centralized Network Configuration.

**CP** Control Plane.

**CQI** Channel Quality Indicator.

**DL** Downlink.

**DS-TT** Device-side TSN Translator.

**eMBB** enhanced Mobile Broadband.

**GBR** Guaranteed Bit Rate.

**GCL** Gate Control List.

**gNB** next generation NodeB.

**IIoT** Industrial Internet of Things.

**Non-GBR** Non-Guranteed Bit Rate.

**NW-TT** Network-side TSN Translator.

**PCF** Policy Control Function.

**PCP** Priority Code Point.

**PDU** Packet Data Unit.

**QFI** QoS Flow Identifier.

**QoS** Quality of Service.

**RAN** Radio Access Network.

**RB** Resource Block.

**ST** Scheduled Traffic.

**TSN** Time-Sensitive Networking.

**UE** User Equipment.

**UL** Uplink.

**UPF** User Plane Function.

**URLLC** Ultra-Reliable Low-Latency Communication.

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# I

# Thesis

# Chapter 1

# Introduction

To meet the rising demands of advanced industrial systems, there is an urgent need for future industrial networks to support deterministic communication, enabling the fast and reliable processes [1]. The physical infrastructure of, e.g., smart factories will require communication technologies capable of delivering critical control functions while supporting advanced automation services. Furthermore, Industrial IoT (IIoT) applications, including autonomous driving, robotics, as well as augmented and virtual reality, demand high data rates and low latency [2, 3]. These applications often require end-to-end latency in the range of milliseconds [4]. Therefore, a dedicated mechanism is needed to address the stringent low-latency requirements in contemporary and future industrial applications. The end-to-end latency refers to a data transmission process that involves a series of network components and protocols to deliver the data from the source to the destination.

The IEEE 802.1 Time-Sensitive Networking (TSN) is a set of standards for Ethernet-based communication[1] that supports the requirements of real-time applications on low-latency wired communication with ultra-low jitter [5, 6]. As a wired network, TSN relies on onboard connections to achieve the determinism and reliability of the network. However, this poses significant constraints for future industrial applications. For instance, wired connection restricts the mobility of vehicles and limits the network coverage only to the areas where

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[1] https://1.ieee802.org/tsn/

physical wired connection is feasible. This lack of flexibility in supporting mobile connections is a critical limitation of TSN. To overcome this limitation, integrating TSN with wireless technologies is seen as vital for contemporary and future industrial applications.

The early generations of mobile networks were not designed to achieve low-latency and reliability. Instead, they address the consumer applications, and does not support many of the requirements of industrial applications. In contrast, the fifth generation of mobile networks (5G) [7, 8] offers the reliability and scalability necessary to meet the demands of these applications, while paving the way towards the development of 6G, which promises even greater advancements in speed, connectivity, and performance [9]. The key characteristics of 5G include ultra-low latency, high data rates, and massive device connectivity, among others. 5G offers a range of services tailored to meet the diverse requirements of advanced industrial applications. The services enabled in 5G include Ultra-Reliable Low Latency Communication (URLLC), enhanced Mobile Broadband (eMBB), and massive Machine-Type Communication (mMTC), all part of the $3^{rd}$ Generation Partnership Project (3GPP) Releases [10, 11].

An integrated wired and wireless network combining TSN and 5G has the potential to meet the real-time requirements, determinism as well as mobility and scalability of communication demanded by contemporary and future industrial applications. A wireless connection is ideal in locations where wired TSN networks are not feasible or practical, resulting in reduced installation and maintenance costs [12]. Wireless networks aim at delivering similar low-latency and high-reliability features that are available with wired TSN, while accommodating applications that require wireless communications [13]. However, wireless networks are not meant to replace TSN or any other wired technology. Instead, 5G and 6G in the future, are expected to co-exist on the same heterogeneous network offering the flexibility and scalability required to meet the demands of future applications. Wired TSN networks will likely be used on the same heterogeneous network for various reasons such as scalable bandwidth and reliable communication regardless of interference. For example, on-board connectivity with capacity of several 100 Mbps will not likely be sent over 5G when the data is mainly needed for local processing.

In order to achieve such an integrated TSN-5G network, a new technology needs to be developed (and evaluated) to bridge diverse techniques and protocols inherent to these standards. 3GPP has included the integration of TSN and 5G since the early Release 16 [14], where 5G appears as a black box to the whole TSN network, providing the basic means for the integration. However, there are still gaps for investigation on this interaction since there are different approaches and aspects, which remain unclear to both the research community and industry stakeholders. As such, the implementation of the necessary functionalities has been left open for exploration by the research community. This thesis aims to contribute to that exploration.

Figure 1.1 illustrates an application of the integrated TSN-5G network, where TSN is used within vehicles and 5G is used among the vehicles and their control center. Within each vehicle, TSN runs over wired switched Ethernet, managing the transmission of various data traffic from sensors, cameras, and various computing units. For such data transmission, TSN utilizes the VLAN IEEE 802.1 frame format, where the priority code point (PCP) field corresponds to the priority level of the TSN flow. A traffic flow refers to a sequence of packets sent from a common source to a common destination characterized from the same Quality of Service (QoS) requirements, e.g., specified as tolerances on latency, bandwidth, and packet error rate, among others. Moreover, TSN assigns flows to various traffic classes starting from Best Effort (BE) to the Scheduled Traffic (ST). A proper scheduling decision is calculated by the use of two traffic shapers which assign the critical and non-critical traffic to different time slots. In addition, some of the TSN traffic has to be sent to the remote control center to support the concept of collaborating vehicles, or the remote control of quarries in dangerous areas such as mines.

Traversing traffic from the TSN network to the 5G network, necessitates the development of a gateway that serves as an interface between both TSN and 5G networks ensuring the end-to-end QoS required in integrated TSN-5G networks. The end-to-end QoS refers to the ability of a network to support the end-to-end transmission of traffic flows with consistent QoS-es across multiple interconnected and diverse network technologies such as wired TSN and cellular 5G. Moreover, scheduling 5G radio resources for data transmission presents significant challenges due to the time-variant characteristics of wireless connections, which has implications on the data propagation latency, jitter and reliability of the transmissions [15].

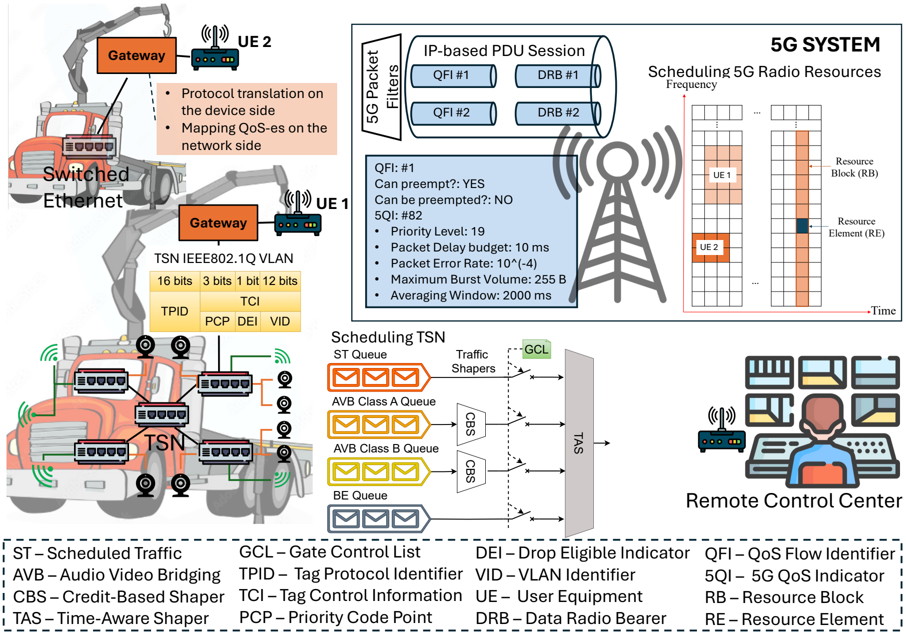

Figure 1.1: The conceptual view of collaborating vehicles utilizing integrated TSN-5G networks.

***Scope of the thesis.*** This thesis aims to support the integration of TSN and 5G networks by developing the necessary translation techniques that function as a gateway that forwards traffic from the TSN network to 5G and vice-versa. The proposed gateway is implemented and evaluated on a real TSN-5G setup. Moreover, the thesis studies the 5G QoS profiles to manage the end-to-end QoS requirements among the integrated TSN-5G network. Lastly, the thesis addresses the allocation of 5G radio resources for the transmission of TSN flows with stringent timing requirements, considering the time-variant characteristics of the 5G wireless connections. A detailed discussion of these challenges is provided in the following Chapter.

## 1.1 Thesis outline

This thesis consists of two main parts. The first part provides an introduction to the overall work, where Chapter 2 presents an overall research overview consisting of the research challenges, the main research goal refined into sub-goals, as well as the research methodology. Chapter 3 introduces background information on the research area. Chapter 4 introduces the corresponding technical contributions, and finally Chapter 5 draws the final conclusions and present an outlook on future work. A collection of five research papers constitutes the second part of the thesis that describes the research results.

# Chapter 2

# Research Overview

## 2.1 Technical Challenges

Although the integration of TSN and 5G networks is part of the $3^{rd}$ Generation Partnership Project 3GPP specifications, there are still gaps for further investigation on this integration since there are different approaches and aspects that remain unclear to both the research community and industry stakeholders. This thesis is motivated by the following existing research challenges within the integration of TSN and 5G mobile networks.

**Design and Evaluation of TSN-5G Architectures**. The TSN-5G integration presents a significant challenge due to the fundamental differences between the TSN's Ethernet-based communication and 5G's cellular technology. Since the TSN network operates on Layer 2 of the OSI model, while 5G operates on Layer 3, there is a gap that prevents direct communication. 3GPP recommends an architecture where the 5G system is represented as a logical TSN bridge and appears as a black box for the whole TSN network. Such integrated TSN-5G architecture requires translation functionalities to forward the traffic from the wired to the wireless network and vice-versa. The 3GPP Release 18 [10] standardizes these translation functionalities into three parts: 1) DS-TT function, which resides on a UE side of 5G network, 2) NW-TT function, which resides in the User Plane Function (UPF) side (both on the user plane), and 3) TSN Application Function (TSN AF), which resides on the control plane and is used to influence traffic routing in the user plane based on QoS mapping of TSN QoS-es to the 5G QoS profiles. However, the detailed design and implementation of these functionalities has been left open for exploration by the research community.

To ensure compatibility within the TSN-5G network, a gateway is needed for translating communication protocols used in TSN and 5G networks. This guarantees seamless interoperability between the networks while maintaining QoS, ensuring low-latency communication and reliable data transmission. However, the implementation of an integrated TSN-5G setup on an actual hardware poses an additional challenge due to limited device availability and compatibility issues. Although 3GPP specifications provide the necessary means for the TSN-5G integration, the operation of such integrated TSN-5G network in low-latency applications remains an open topic to the research community.

**QoS Configuration and Mapping Strategies**. As we transit to integrated wired and wireless networks, the current state of technology is insufficient to ensure QoS across the entire network [16]. Achieving end-to-end QoS management and seamless traffic forwarding with real-time requirements between TSN and 5G demands the development of new techniques to overcome the fundamental dissimilarity of the considered systems.

To enable integrated TSN-5G networks, it is important to ensure that both wired and wireless technologies can meet the QoS requirements of industrial applications such as low-latency, and high bandwidth, among others. TSN guarantees the requested QoS-es to high critical traffic by assigning different priorities to the traffic flows, and defining various traffic shapers. On the other hand, 5G Radio Network assigns different 5G QoS Indicators (5QI) to each traffic flow. The 5QI is a scalar that represents one of the 5G QoS profiles used to manage the allocation of traffic flows for both uplink and downlink transmission. These QoS profiles include parameters such as priority, Packet Delay Budget (PDB), Packet Error Rate (PER), and Maximum Data Burst Volume (MDBV), among others. It is important to mention that the priority used in TSN flows is different from the priority level assigned in the 5G QoS profiles. Bridging these disparities is essential to enable the seamless integration of both technologies.

However, the support for different QoS modelling of 5G and TSN to ensure deterministic and bounded low-latency remains an open challenge [17]. To ensure the applications' requirements across the entire TSN-5G network, there is a need for a proper QoS configuration and mapping among TSN traffic classes and priorities to the 5G QoS profiles, and vice versa.

**Scheduling 5G Radio Resources to TSN flows**. Although 3GPP recommends the appearance of 5G as a black box for the TSN network, the requested deterministic communication of TSN flows over wireless 5G channel represents complex challenges. One of the challenges in 5G is the design of a flow-based scheduler at the 5G base station (referred to as the gNB, next-generation node B [18]) to meet per-flow guarantees, in particular those flows that are transmitted from the wired TSN network. The real-time flow scheduling in 5G New Radio (NR) intertwines (a) the radio resource allocation in the frequency and time domain to multiple users/flows appropriately; (b) determining the amount of data that can be transmitted by each user/flow in the spatial domain considering the interference from the other devices or obstacles; and (c) the selection of the Modulation Coding Scheme (MCS) to satisfy the requirements of TSN flows, making the problem drastically challenging [19].

A flow-based radio resource scheduling approach is needed for transmitting TSN flows over 5G to meet the latency requirements of real-time applications that utilize both TSN and 5G. Ensuring real-time guarantees to flows coming from the TSN network becomes even more challenging as the real-time flows are sensitive to the time-variant characteristics of the wireless 5G channel. On the other hand, the allocation of radio resources, such as time slots and frequency bands, for TSN flows with hard real-time constraints while co-existing with less-critical flows introduces complexities. Moreover, as 5G radio resources are limited, there is a need to efficiently manage these resources while achieving a feasible scheduling solution for the transmission of TSN flows over the 5G network.

## 2.2 Research Goals

This thesis aims to integrate the TSN and 5G networks by providing translation techniques, managing the end-to-end QoS requirements, and addressing the allocation of 5G radio resources to TSN flows with stringent timing requirements, which are crucial for ensuring reliable, deterministic, and low-latency communication with real-time requirements.

Based on the technical challenges presented in Section 2.1, we have identified the following scientific research goal:

> **Overall Research Goal (RG):** *To facilitate end-to-end real-time communication in integrated TSN-5G networks, ensuring end-to-end QoS and efficient utilization of 5G radio resources for the transmission of real-time TSN flows.*

The overall RG can be refined into four sub-goals ($\boldsymbol{RG_i}$) as follows:

$\boldsymbol{RG_1}$: Identify challenges and opportunities in the state-of-the-art on the integration of TSN and 5G networks.

$\boldsymbol{RG_2}$: Develop and evaluate the translation techniques to forward traffic seamlessly between TSN and 5G.

$\boldsymbol{RG_3}$: Develop a framework to map QoS requirements between TSN and 5G networks, ensuring consistent performance across the integrated TSN-5G system.

$\boldsymbol{RG_4}$: Develop the scheduling techniques needed for the allocation of 5G radio resources, satisfying the latency, and bandwidth requirements of real-time TSN flows under varying 5G network conditions.

## 2.3 Research Methodology

To address the research goal presented earlier, this work uses the hypothetico-deductive [20] research method for computer science. It also considers the systematic literature review [21] as a formal method to investigate the research area and construct a well-structured design model for TSN and 5G integration. Additionally, it considers implementing the idea in real use cases provided by some industrial partners to show the effectiveness of the proposed solutions.

Moreover, the performance of the proposed solutions is demonstrated on simulation and experiments on an actual hardware setup. The overall research process is presented in Figure 2.1.

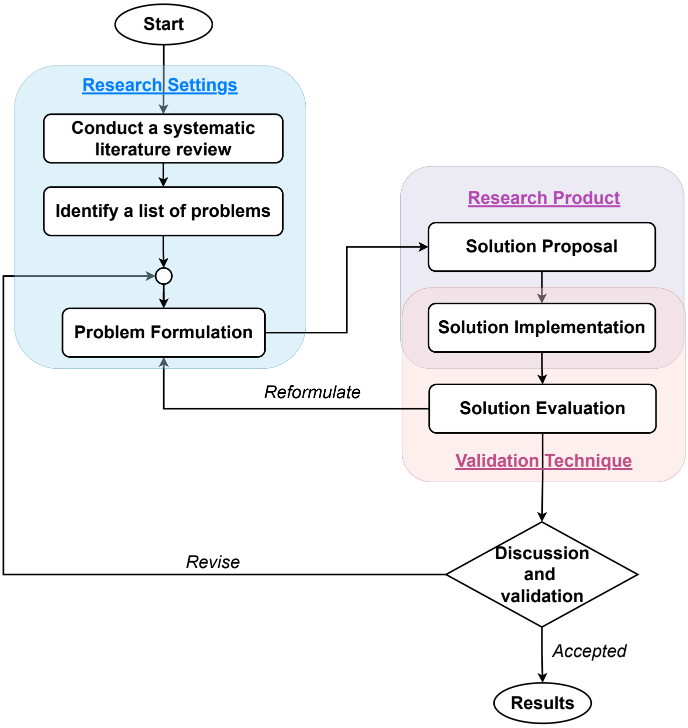

Figure 2.1: Research process.

The research process consists of the following steps:

1. **Systematic Literature Review:** A systematic literature review (SLR) [21] was conducted in order to achieve a comprehensive and well-structured snapshot of the existing research on TSN-5G integration. The existing literature was explored to understand different aspects of such integration, and thus technical characteristics and potential gaps in the

state-of-the-art were identified.

2. **Identify a list of problems:** We identify gaps in the state of the art and highlight future research directions, resulting in a list of problems that need to be solved.

3. **Problem Formulation:** From the list of problems, we choose a specific problem and formulate it based on well-structured research sub-goals.

4. **Solution Proposal:** Innovative and novel solutions were discussed and proposed to address the identified problem. The implementation challenges of the solutions were identified. From the discussions, the solution that tackled the problem and overcame the drawbacks of the other solutions was selected for the next step.

5. **Solution Implementation:** The solutions from the previous stage were implemented. Practical challenges were identified, and re-usability of the implemented solution was taken in consideration.

6. **Solution Evaluation:** The solution was evaluated through sets of experiments, use cases, simulation approaches, or theoretical analysis methods. The use cases were taken from the vehicular domain, and some of them were also proposed by our industrial partners: HIAB[1], and Arcticus Systems[2].

7. **Discussion and Validation:** This research was conducted as a joint collaboration with industrial partners mentioned before. Therefore, we received the industrial partners' feedback based on continuous discussions. The results from the evaluation were discussed thoroughly and their validity were examined. If the results were judged as inconvenient, we revised our solution or proposed a new one by reiterating the process. Finally, if the results were accepted, the research process was ended by publishing the proposed solution in a peer-reviewed article.

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[1] https://hiab.com/en

[2] https://www.arcticus-systems.com/

# Chapter 3

# Background and Related Work

This chapter describes the background for the work presented in this work together with a list of related works that will help the reader understand the basic concepts used throughout this thesis.

## 3.1 Ethernet-based Communication

Ethernet is a communication standard for Local Area Networks (LAN), Metropolitan Area Networks (MAN) and Wide Area Networks (WAN). It includes specifications for both the physical and data link layer of the OSI model. The data link layer is divided into two sub-layers: Logical Link Control (LLC) and Medium Access Control (MAC). The LLC acts as a bridge between the physical layer, MAC layer and the Network layer. It controls the logical links between end stations and makes sure that multiple network protocols can be supported on the same multipoint network. MAC layer handles the hardware side with each Network Interface Card (NIC) having a unique 48-bit address often represented in hexadecimal. It is responsible for interactions with the physical medium. Ethernet technology assigns dedicated priorities to each frame based on IEEE 802.1Q standard. To introduce real-time capabilities, additional features have been added, such as Time Division Multiple Access (TDMA), polling based communication, and summation frame communication [22]. This set of extensions fulfill the stringent real-time requirements, but they require modifications to the IEEE Ethernet MAC [23]. Therefore, the Audio-Video Bridging (AVB) working group broadened in scope [24] following rising demand from industries for high reliability and high bandwidth traffic over Ethernet. In 2012, the AVB working group was renamed to Time-Sensitive Networking (TSN) task group to reflect the expanded scope and the technology's ability to provide reliable and deterministic networking for a wider range of time-sensitive applications beyond just audio and video.

## 3.2 Time-Sensitive Networking

TSN is a set of standards that enable the reliable and deterministic transmission of time-sensitive data over Ethernet. It supports high-bandwidth and low-latency communication, gaining attention in time-critical industrial applications such as in the industrial automation [6] and automotive domains [25, 26]. To improve the Quality of Service (QoS) of Ethernet, the TSN task group proposed several features; e.g, time-aware traffic shaper (IEEE 802.1 Qbv), clock synchronization (IEEE 802.1AS), frame preemption (IEEE 802.1Qbu), and path control and reservation (IEEE 802.1Qca), among others.

### 3.2.1 Traffic Forwarding and Traffic Classes in TSN

TSN switches support 8 different priorities for different types of traffic. The priority is defined by Priority Code Point (PCP) field. The PCP is a 3-bit value added in the 802.1Q-2018 VLAN tag, as shown in Figure 3.1. The VLAN tag consists of two main parts: Tag Protocol Identifier (TPID), and Tag Control Information (TCI). TPID is a 16-bit field set to a value of 0x8100 to indicate that the frame contains a VLAN tag. The TCI includes other sub-fields such as Drop Eligible Indicator (DEI), and the VLAN Identifier (VID). TSN switches use the PCP value to classify incoming frames into different priority levels and apply the necessary mechanisms, such as traffic shaping, prioritization, and reservation, to ensure that time-sensitive data is transmitted with the required accuracy and reliability.

The available scheduling mechanisms in TSN include: (i) Credit-Based Shaper (CBS) for AVB, and (ii) Time-Aware Shaper (TAS), among others,

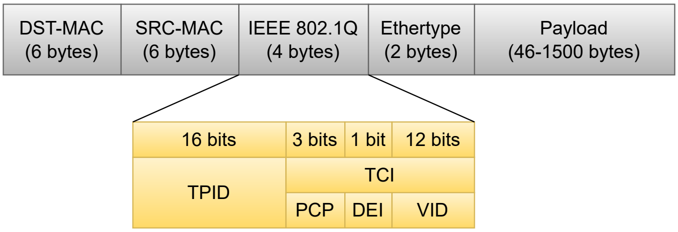

Figure 3.1: TSN frame format.

which allow arbitration of traffic at the egress port.

**TSN traffic classes:** TSN supports three different traffic classes: (1) Scheduled Traffic (ST), (2) Audio Video Bridging (AVB) with Class A and Class B, and (3) Best Effort traffic (BE), presented in Figure 3.2. Each queue is controlled by a Gate Control List (GCL), where all the offline schedule is timestamped. For example, the GCL could specify that flows with a certain priority should be passed through the switch without delay, while flows with a lower priority should be buffered or discarded.

- The ST class is scheduled offline, with strict temporal isolation achieved with the Time-Aware Shaping (TAS) mechanism controlled by the GCL [27]. The GCL is predefined with the specific time slots. When a gate has an open state, the corresponding queue is allowed to send messages over the link. This makes ST class fully deterministic, with no jitter on delivering the messages.

- AVB defines two or more priority classes, starting with Class A as the highest priority queue. The AVB traffic queues are controlled by the CBS [28]. The CBS works on credit basis, and thus the queue consumes credit when it sends a message, and it replenishes the credit when it has a pending message. The traffic from an AVB queue can be transmitted only if the queue has a non-negative credit and if the gate has an open state.

- The BE traffic class consists of non-critical data with no real-time guarantees. It is the lowest-priority class, and traffic from this queue can be sent only if the gate is opened.

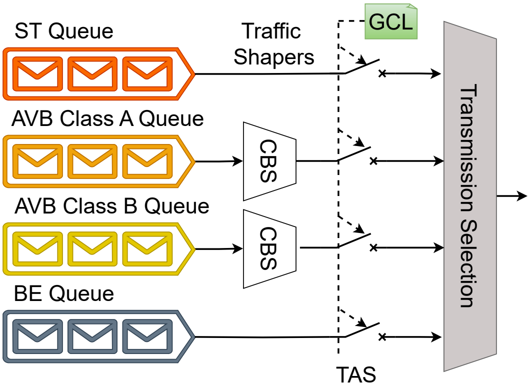

Figure 3.2: An example of traffic forwarding in a TSN egress port.

### 3.2.2 Limitations of TSN

Although TSN is a promising technology for building low-latency, high-bandwidth, and highly-reliable networks for time-sensitive data, there are several missing features that must be overcome in order to fully realize the potential of TSN. TSN is still a relatively new technology, and there is a lack of widespread adoption, particularly in consumer markets. This can limit the availability of TSN devices and make it difficult for users to find compatible products. Although the TSN standardization is evolving, currently there is a lack of interoperability between different TSN implementations, which can lead to compatibility issues and increased complexity when building large-scale TSN networks that include devices from multiple vendors.

Furthermore, as a wired technology, TSN is constrained to areas where cable connections are feasible, lacking the flexibility offered by mobile connectivity. This limitation restricts the applicability of TSN in scenarios that require mobility, such as autonomous vehicles or industrial drones.

## 3.3 Evolution of Mobile Networks

Over the past four decades, the evolution of mobile networks has progressed through five generations, as shown in Figure 3.3. The pre-cellphone era before the 1980s is marked as the zeroth-generation (0G) of mobile communication networks [29]. The evolution starts with the first generation (1G) technology, which was launched in 1980's, introducing wireless voice data through analog mobile technology. The transition of mobile networks from analog to digital communication was marked with the second generation (2G) which supported short message services, followed by the third generation (3G) of mobile networks which improved mobile broadband services and enabled new applications such as video calls, and multimedia message services. In 2010, the evolution of the technology arrived to the fourth generation (4G) based entirely on Internet Protocol (IP), which improved mobile broadband services and introduced services such as high definition video streaming and mobile gaming.

Finally, from 2020 we are experiencing the fifth generation (5G) designed to achieve low latency and reliability, providing the built-in flexibility required by Industry 4.0. The development of fifth generation of mobile communications (5G) is standardized by the $3^{rd}$ Generation Partnership Project (3GPP). 5G technology was first introduced in 3GPP Release 15 [14], as a Non-Standalone network with the ability to utilize existing LTE and EPC (from 4G) infrastructure, thus making new 5G-based radio technology available without network replacement. 5G capabilities support novel applications such as virtual reality (VR), autonomous vehicles, and IIoT, among others.

However, applications such as holographic telepresence, space tourism and remote surgery traverse the limits of 5G networks, driving the evolution towards the sixth generation of mobile technology (6G) [30].

## 3.4 5G Network

5G network provides significant improvements to the mobile network technology [31, 7]. It is designed to achieve low latency and high reliability, providing the built-in flexibility required by Industry 4.0. 5G includes three generic services: enhanced Mobile Broadband (eMBB), massive Machine-

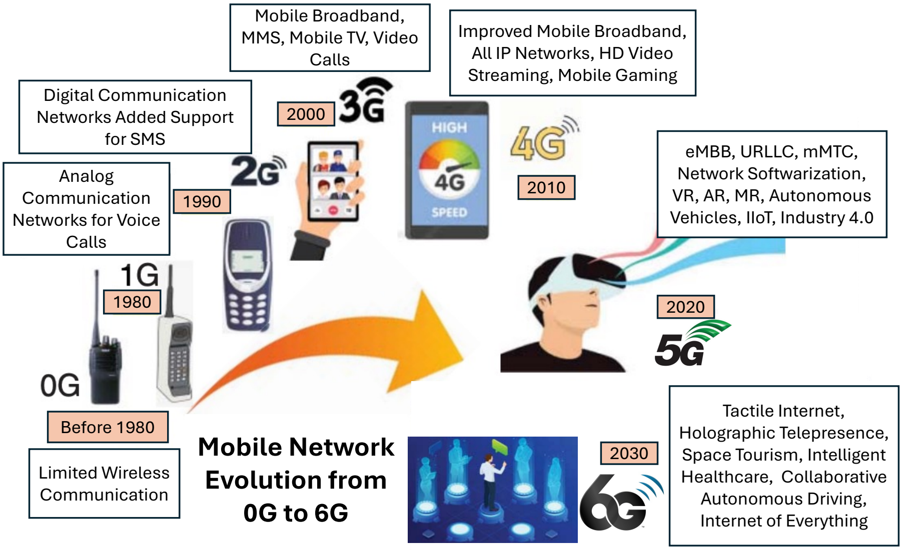

Figure 3.3: Evolution of mobile technology from 0G to 6G. Source: Porombage et. al., "Evolution of Mobile Networks," in Security and Privacy Vision in 6G: A Comprehensive Guide , IEEE, 2023, pp.1-14[29].

Type Communications (mMTC), and Ultra-Reliable Low-Latency Communication (URLLC), [32, 33, 34].

The eMBB supports high data rates, higher user mobility, high density, and fixed-mobile convergence. The mMTC provides efficient connectivity for a massive number of heterogeneous IoT devices with a variety of characteristics and demands. URLLC is a set of features for 5G to support critical applications with low-latency and reliability requirements. The standardization for URLLC started with 3GPP Release 15, and evolved until 3GPP Release 18 [35]. With URLLC features, the new 5G Radio Access Network (RAN) [36] can achieve ultra-low latency and reliability up to 99.9999%. Within the core network, latency is typically below 1 ms [37]. The desired QoS requirements for URLLC depend on the applications as shown in Table 3.1.

Table 3.1: Expected QoS requirements for URLLC [34, 38].

| **Industry** | **Error Rate/Reliability** | **Latency (ms)** |
|---|---|---|
| Augmented/Virtual Reality | $10^{-5}$ - $10^{-3}$ | 5 - 10 |
| Autonomous/guided vehicles | $\geq 10^{-3}$ | 5 - 10 |
| Automated Industry | $10^{-9}$ - $10^{-5}$ | 1 |
| Internet of things/Tactile Internet | $10^{-5}$ | 1 |

### 3.4.1 PDU Session and QoS Flows

5G network provides connectivity to user equipment (UE) towards a Data Network (DN) such as Internet, IP Multimedia Subsystem (IMS), or any private corporate network. To provide this end-to-end connectivity, 5G establishes a Packet Data Unit (PDU) session through the User Plane Function (UPF), containing up to 64 QoS flows. The 5G UPF is the function that connects the actual data coming over the RAN to the Internet.

A 5G QoS flow is assigned to every flow coming to the uplink (UL) or downlink (DL). There are two types of flows in 5G: (i) Guaranteed Bit Rate (GBR) QoS flows and (ii) Non-guaranteed Bit Rate (Non-GBR) QoS flows. GBR flows are traffic flows that are allocated a minimum amount of network resources, ensuring a minimum level of QoS for the traffic. The GBR transmission is used for applications when providing real-time services, as there are no problems associated with overload during transmission of this data and packet loss [39]. Non-GBR flows are best-effort flows that do not have a guaranteed level of network performance. They are used for applications that are less critical or have more flexible requirements.

The QoS flow is the finest granularity of QoS differentiation inside a PDU session. It has a unique QoS Flow Identifier (QFI). The traffic with the same QFI within a PDU session will receive the same traffic forwarding treatment [40]. Flows coming from different applications are classified or mapped to suitable QoS flows by the UPF in case of DL, and by the UE in case of UL.

### 3.4.2 5G Packet Filtering

Packet filtering is a technique used in 5G to manage and control network traffic by filtering the UL (incoming) and DL (outgoing) packets based on predefined rules. This helps to ensure that only authorized traffic is allowed through the network, and can help to prevent security threats and other types of unwanted traffic. Figure 3.4 describes the process of packet filtering inside 5G. The data packets from the applications arrive on both sides: on the UE side in case of UL and on UPF side in case of DL. 5G applies QoS Rules mapping the UL packets to QoS flows on UE side, and Packet Detection Rules (PDRs) to map DL packets to QoS flows on UPF side. Both QoS Rules and PDRs use some Packet Filter Sets in order to identify one or more IP or Ethernet flows.

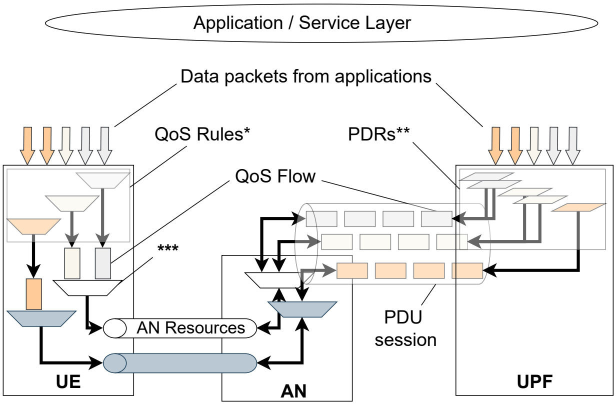

Figure 3.4: Packet classification, user plane marking and mapping to radio resources [10].

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- QoS Rules* - mapping UL packets to QoS flows in UE and apply the QoS flow marking
- PDRs** - Packet Detection Rules classifying DL packets for QoS flow marking in UPF
- *** - Mapping QoS flows to Access Network (AN) or radio resources

The 3GPP Release 18 defines two types of Packet Filter Sets: (i) IP Packet Filter Set, and (ii) Ethernet Packet Filter Set. The IP Packet Filter Set is a combination of fields such as Source/Destination IP address or IPv6 prefix; Source/Destination port number or port ranges; Protocol ID of the protocol above IP/Next header type; Type of Service (TOS) (IPv4) or Traffic class (IPv6) and Mask; Flow Label (IPv6); Security parameter index; and Packet Filter direction [10].

An Ethernet Packet Filter Set is a combination of Source/destination MAC address (may be a range); Ethertype as defined in IEEE 802.3; Customer-VLAN tag (C-TAG) and/or Service-VLAN tag (S-TAG) VID fields as defined in IEEE Std 802.1Q; Customer-VLAN tag (C-TAG) and/or Service-VLAN tag (S-TAG) PCP/DEI fields as defined in IEEE Std 802.1Q; IP Packet Filter Set, in the case that Ethertype indicates IPv4/IPv6 payload; and Packet Filter direction [10]. For an Ethernet PDU Session, the Packet Filter Set shall support Ethernet Packet Filters based on the above combination of fields. When a TSN flow reaches 5G system either on UL, or DL side, an Ethernet Packet Filter Set should be supported. Once a Ethernet PDU session is established a 5G QFI should be assigned to every application flow.

### 3.4.3 QoS Identifier Insertion

Considering the DL direction, the insertion of QFI is performed on the UPF by the Session Management Function (SMF). The SMF extracts the QoS flow binding parameters (in the following section) and creates a new QoS flow if the one requested does not exist. Each application gets its own Service Data Flow (SDF) inside the UPF, and then they are associated/mapped to different or same QFI based on their QoS needs as shown in Figure 3.5. The QoS realization for downlink packets in 5G is achieved through the use of several protocols and procedures, including Service Data Flow (SDF) and Service Data Adaptation Protocol (SDAP). A similar approach is used for UL packets.

SDF is a mechanism used in 5G to ensure the appropriate priority level and resources that should be allocated to different packets based on their QoS-es. SDAP is a protocol used in 5G networks to adapt the packet headers of downlink packets by including information about the SDF and QFI associated with the packet. Another mapping is performed on the radio side, assigning QoS flows to Data Radio Bearers (DRB) which are used to carry user data between the UE and the gNB.

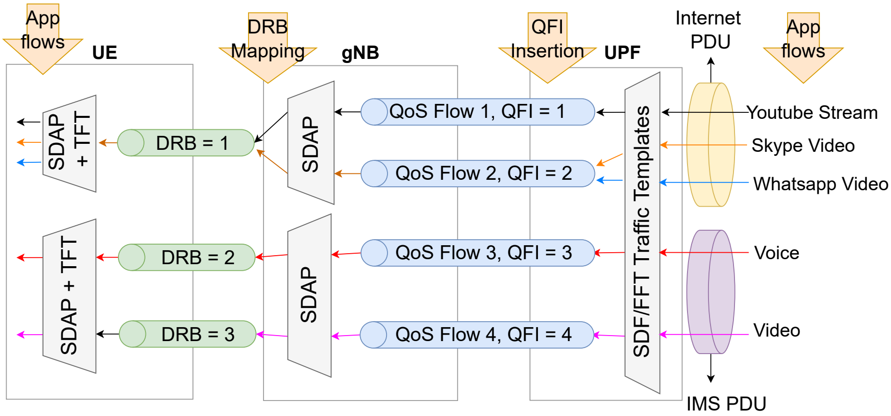


Figure 3.5: Example of QoS realization for downlink packets. Source: Rodini 2017, slide 6 [41].

### 3.4.4 5G Radio Resource Management

5G network assigns a 5G Quality of Service Identifier (QFI) to each flow coming from the connected user equipments (UEs). The UE is a device capable of connecting to the 5G network. On the other hand, the 5G base station (gNB) allocates a set of radio resources to connected UEs depending on the requested QoS requirements. The 5G radio resource grid, also known as the physical resource grid, refers to the division of radio resources in the time and frequency domains as depicted in Figure 3.6. The time domain is divided into slots, where the slot duration depends on the configured 5G numerology ($\mu$). 5G uses Orthogonal Frequency Division Multiplexing (OFDM) symbols as the basic data transmission units. The frequency domain is divided into multiple subcarriers which occupy a specific frequency band. The numerology is a scalar that defines the subcarrier spacing (SCS), e.g., $\mu = 0$ refers to SCS=15 kHz, as shown in Table 3.2.

The combination of subcarriers with the time slots creates a grid structure in 5G in which the gNB needs to make scheduling decisions based on different scheduling algorithms to allocate a specific set of radio resources to each connected UE. The finest granularity of the 5G resource grid is the resource el-

| $\mu$ | **Subcarrier Spacing (SCS)** | **Resource Block Bandwidth** | **Slots per Sub-Frame** | **Slot Duration** | **OFDM Symbols per Slot ($N_{symb}^{slot}$)** | **Symbol Duration** |
|---|---|---|---|---|---|---|
| 0 | 15 kHz | 180 kHz | 1 | 1 $ms$ | 14 | 71.43 $\mu s$ |
| 1 | 30 kHz | 360 kHz | 2 | 0.5 $ms$ | 14 | 35.71 $\mu s$ |
| 2 | 60 kHz | 720 kHz | 4 | 0.25 $ms$ | 14 | 17.86 $\mu s$ |

Table 3.2: 5G supported transmission numerologies for Sub-6 GHz (FR1).

ement (RE), which consists of one subcarrier in the frequency domain and one OFDM symbol in the time domain. A set of 12 adjacent subcarriers is called a Resource Block (RB). The allocation of RBs is controlled dynamically by the gNB based on the UE's QoS requirements, network conditions, and traffic load. The 5G resource grid consists of $N_{RB}^{\mu}$ RBs in the frequency domain, and $N_{symb}^{slot} \cdot 2^{\mu}$ symbols in the time domain, as shown in Figure 3.6.

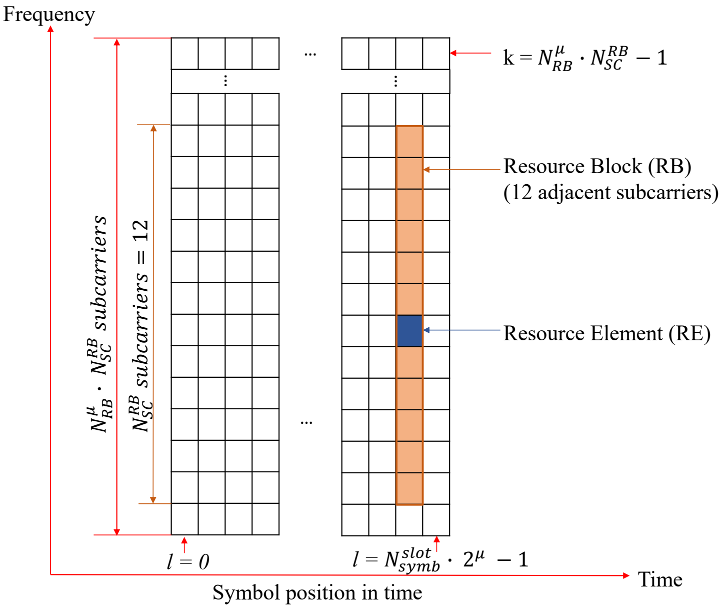


Figure 3.6: Representation of 5G Resource Grid.

### 3.4.5 Control Exchange Information in gNB-UE Communication

Each UE connected to the 5G network has a specific set of QoS requirements which are taken into account when transmitting the traffic flows via the 5G. The active UEs send a scheduling request via the control channel to the base station asking for specific QoS requirements, as shown in Figure 3.7. In this request, the UE specifies the amount of data to be transmitted, the timing constraints, and the Channel Quality Indicator (CQI), which is a parameter that provides information on the quality of the wireless channel between a connected UE and the gNB. The gNB, after evaluating the request, responds back with a scheduling grant specifying the reserved portion of radio resources for each connected UE. It performs different scheduling techniques to optimize the use of radio resources while maximizing the throughput and achieving the requested timing constraints of the traffic flows.

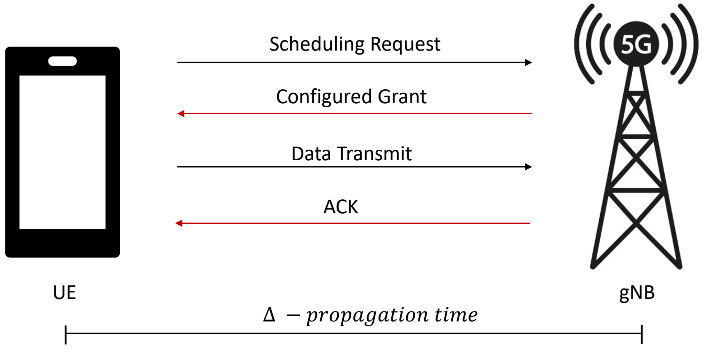


Figure 3.7: The process of sharing control information between UE and the gNB.

The amount of data that a UE can transmit within a set of RBs depends on the CQI value and the Modulation Coding Scheme (MCS) being used. The CQI value is a parameter used to indicate the quality of the wireless channel between a connected user and the gNB. It provides information related to network conditions including the signal-to-noise ratio (SNR), signal quality, and interference levels [42]. The higher CQI represents a better channel quality, meaning less air interference from other devices, or obstacles and allowing for higher data rates and more reliable communication. Conversely, the lower the CQI value the poorer the channel conditions resulting in lower data rates and a higher packet loss rate.

The quality of the wireless channel between the UE and the gNB differs depending on many factors such as interference from Line-of-Sight (LOS) and Non Line-of-Sight (NLOS) obstacles or from other devices, mobility of a moving vehicle, weather conditions, as well as the distance of the UE from the 5G antenna [43, 44, 45], as shown in Fig. 3.8.

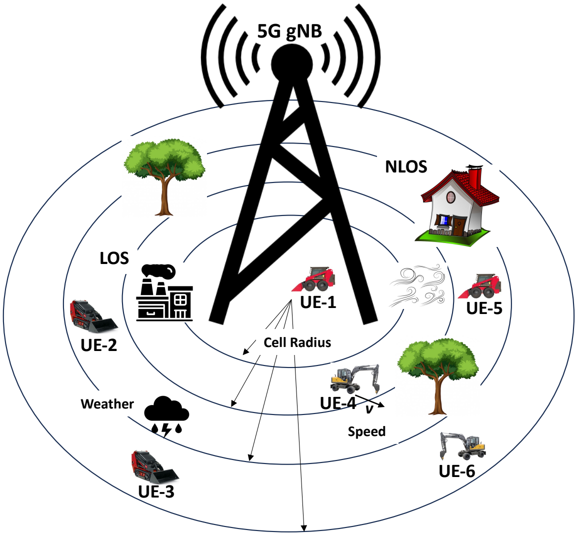


Figure 3.8: The 5G gNB coverage area and parameters that can affect the wireless channel quality.

### 3.4.6 Private 5G Network

Private 5G refers to a dedicated 5G network with enhanced communication characteristics designed for the exclusive use of a factory, or organization. Reusing the 5G technology, private 5G networks are characterized by high availability, ultra-low latency, high reliability, and scalability for numerous devices [46]. Moreover, it is an isolated network, also known as a standalone non-public network (SA NPN 5G), that restricts wireless connectivity only to the authorized devices, therefore minimizing the wireless interference from unknown devices. More importantly, it allows the owner to totally control every aspect of the network, enabling customized configurations for specific use cases and performance requirements such as low latency, high throughput, and availability, among others [46, 47]. The key enabling advancements and technologies for private 5G networks include spectrum management, URLLC, integration with TSN, network slicing, interference management, localization and tracking, and private edge computing [46].

The deployment of the private 5G network, including the 5G core network, is depicted in Figure 3.9. All network functions are contained inside the logical boundaries of the defined premises (e.g. factory) and the private network operates independently from the public network [48]. The subscriber database stores the information about the users that can access the network including user credentials and subscription information. The control plane handles tasks such as mobility management, session management, and network access control. In addition, the user plane is responsible for the actual data transmission within the network. It handles the transmission of the IP data traffic between UEs and the external networks. The 5G core network is responsible for managing both the control plane and user plane functions.

The GTP-U protocol is utilized to enable the transmission of user data across 5G network, enabling seamless connectivity and data transmission. Moreover, the Differentiated Service Code Point (DSCP) can be used to mark and prioritize packets carried within GTP-U tunnels. DSCP is a field in the IP header used to identify and classify packets based on the type of service required [49]. Integrating 5G with TSN networks involves a proper mapping of the DSCP of a 5G packet to the TSN PCP values, and vice versa to ensure end-to-end QoS continuity.

## 3.5 5G as a Logical/Transparent TSN Bridge

The integrated TSN-5G architecture supported from 3GPP Release 18 [10] is presented in Figure 3.10. In this architecture, 5G system is represented as a log-

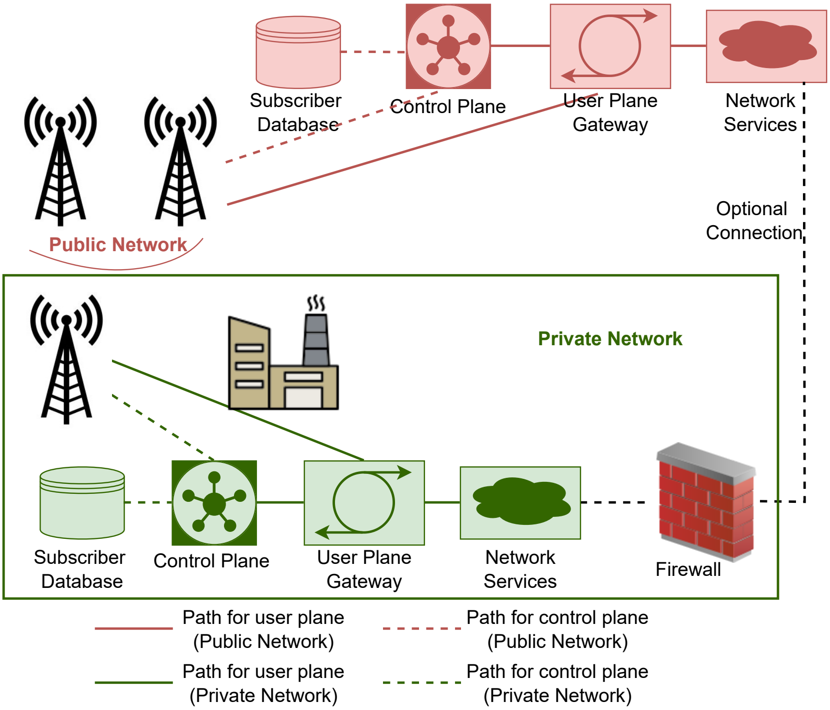


Figure 3.9: The private 5G network deployment.

ical TSN bridge and appears as a black box to the TSN system. To secure the inter-operation between both systems, there is a need for the TSN translators for both user plane and control plane. There are three translators in TSN-5G architecture: 1) Device-side TSN Translator (DS-TT), 2) Network-side TSN Translator (NW-TT), and 3) TSN Application Function (TSN AF). The DS-TT and NW-TT handle the physical and protocol translation on the device and network sides. They perform functions such as protocol translation, time synchronization, per-stream filtering and policing, traffic mapping based on the control information provided in TSN AF and Policy Control Function (PCF). Whether DS-TT and UE are combined or are separate is up to implementation [10]. The TSN AF is part of the 5G core network and provides the control plane translator functionality for managing and coordinating the integration between the 5G QoS framework and the TSN domain. It communicates with the PCF to ensure that the TSN traffic requirements are properly reflected in the network policies, 5G QoS profiles, and resource allocations.

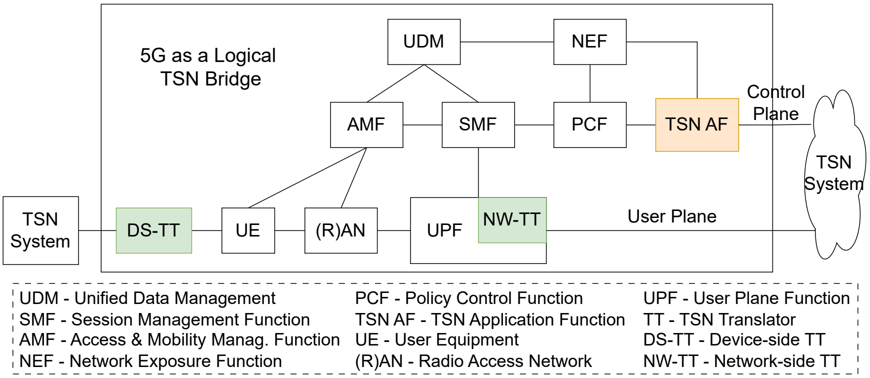


Figure 3.10: The integrated TSN-5G architecture, where 5G appears as a logical TSN bridge.

The following concepts are part of the core architecture for a TSN-5G design presented also in Figure 3.10; a brief overview is given to better understand the function of the individual components.

- Control Plane (CP) – Definition of a plane that handles connection management, QoS policies, authentication, and other management functions, separated from the UP.

- Access and Mobility Management Function (AMF) – Receives information related to 5G sessions within the network and manages handovers between gNB components [50].

- Unified Data Management (UDM) – Follows the design of the Home Subscriber Service (HSS) in 4G networks. It stores user data information regarding what components are connected to the network, customer data, and customer information. The 5G additions to the HSS have added cloud functionality to the 5G designs.

- Session Management Function (SMF) – Creates a communication channel between the CP and the UP. It handles the UPF concerning session context by dealing with creating, updating, and deleting PDUs. It communicates with the TSN AF via the PCF, giving the MAC addresses of the TSN Translators per PDU session.

- Network Exposure Function (NEF) – Provides a secure connection between 5G and third-party applications. Communication with 5G services is done via the NEF.

- Policy Control Function (PCF) – Receives the QoS information from the TSN AF, and maps the TSN QoS parameters to a 5QI. The 5QI is a scalar reference to certain 5G QoS characteristics, such as priority, Packet Delay Budget (PDB), Packet Error Rate (PER) and Maximum Data Burst Volume (MDBV).

- Application Function (AF) – Communicates with the TSN Centralized Network Configuration (CNC) unit, with the primary purpose to decide TSN QoS parameters, such as priority and delay based on received configuration information from the CNC.

- User Plane (UP) – Definition of the plane which deals with data-traffic forwarding, separated from the CP.

- TSN Translator (TT) – Both the DS-TT and the NW-TT acts as intermediaries between the user plane borders of the logical TSN bridge. The Device Side refers to, e.g., actuators or sensors, while the Network refers to the TSN network on the other side of the logical TSN bridge. In essence, they translate the requirements established by the AF and PCF on the flows traversing the logical TSN Bridge [51].

- User Plane Function (UPF) – The communication scheme established between the gNB and the NW-TT.

- User Equipment (UE) – Components capable of communicating with the RAN.
- Radio Access Network (RAN) – A 5G capable device which acts as the access point for the wireless side of the logical TSN bridge, sometimes also known as next generation Node B (gNB). It communicates with one or many UEs.

# Chapter 4

# Research Contributions

In this chapter the contributions and included papers are described.

## 4.1 Research Contributions

This thesis makes the following research contributions to address the outlined research goals:

> ***$RC_1$* – A systematic literature review on the TSN-5G integration**: We perform a comprehensive investigation of the state-of-the-art in TSN-5G integration, accompanied by the development of a structured and focused classification scheme for relevant publications. This contribution aims to assist researchers and practitioners in identifying and understanding existing solutions and their applicability in industrial environments. Furthermore, it facilitates the identification of research gaps and highlights opportunities for further research in the area of TSN-5G integration.
>
> ***$RC_2$* – Enabling traffic forwarding between TSN and 5G networks**: We develop a technique to enable traffic forwarding between TSN and 5G communication technologies. Moreover, we present a proof-of-concept implementation of the proposed techniques in a commonly used TSN network simulator NeSTiNG [52] that is based on OMNeT++ [53]. We

show that the technique can assist network designers to evaluate various holistic TSN-5G network configurations.

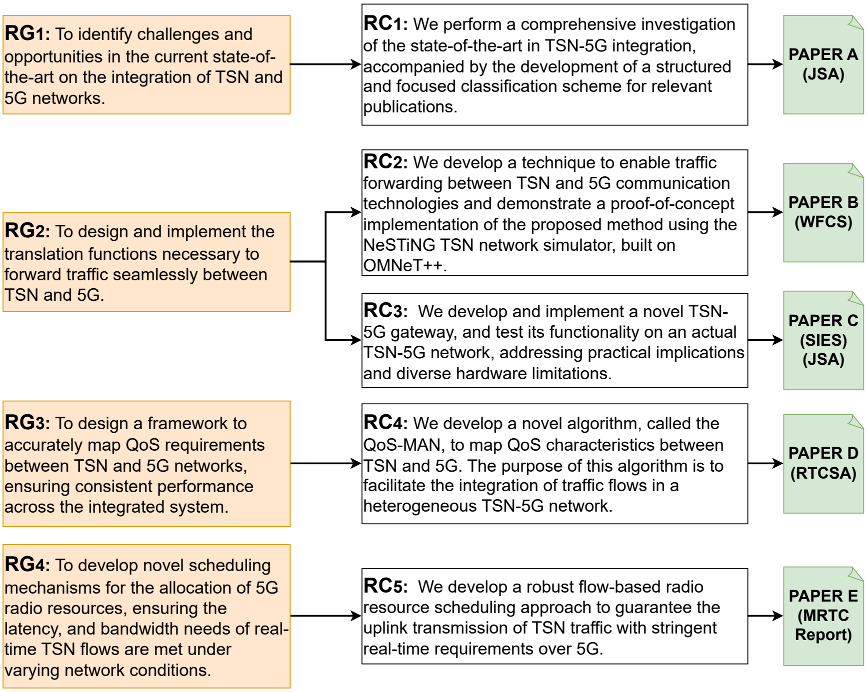
***$RC_3$* – *Development and implementation of a novel TSN-5G gateway***: We develop and implement a novel TSN-5G gateway, and evaluate its functionality on an actual TSN-5G network, addressing practical implications and diverse hardware limitations. The TSN-5G gateway serves as an interface across both networks, handling tasks such as protocol translation, and QoS management, within the integrated TSN-5G network. Our findings indicate that it is possible to achieve latencies under 20 ms in integrated TSN-5G networks, given our specific configuration of a private 5G setup with a channel bandwidth limited to 40 MHz. We also identify the need for the implementation of a proper QoS mechanism to enable the prioritization of high-critical data transmission.

***$RC_4$* – *Mapping TSN traffic requirements to 5G QoS profiles***: We develop a novel algorithm, called the QoS-MAN, to map QoS characteristics between TSN and 5G. The purpose of this algorithm is to facilitate integration of traffic flows in a heterogeneous TSN-5G network. Although we specifically consider TSN as the Ethernet protocol in this mapping, the proposed algorithm can be adapted to the flows between 5G and other Ethernet protocols that provide stringent QoS. The algorithm uses the application requirements as its input in the form of constraints such as the deadline constraint, jitter constraint on delivery of packets, bandwidth constraint, and packet loss rate. Based on such requirements, the QoS-MAN algorithm maps each traffic flow to a specific 5G QoS profile that fulfills its needs.

***$RC_5$* – *Scheduling 5G radio resources to transmit TSN traffic***: We develop a robust flow-based radio resource scheduling approach to ensure the uplink transmission of TSN traffic with stringent real-time requirements over 5G. We propose a two-phase 5G radio resource scheduling approach for the transmission of TSN traffic, ensuring the hard real-time requirements of ST traffic, while scheduling AVB traffic with soft timing requirements. The first phase consists of the offline scheduling of 5G radio resources for ST flows to ensure hard real-time guarantees, whereas the second phase utilizes the remaining radio resources, at run-time, to schedule AVB flows while considering 5G channel fluctuations, which have an impact on the uplink transmission's reliability and capacity.

## 4.2 Overview of the Included Papers

The main contributions of the thesis are organized and presented as a collection of five included papers. The mapping of the aforementioned research goals and thesis contribution into publications, that will be included in the thesis, is shown in Figure 4.1.



**RG1:** To identify challenges and opportunities in the current state-of-the-art on the integration of TSN and 5G networks.

**RC1:** We perform a comprehensive investigation of the state-of-the-art in TSN-5G integration, accompanied by the development of a structured and focused classification scheme for relevant publications.

**RG2:** To design and implement the translation functions necessary to forward traffic seamlessly between TSN and 5G.

**RC2:** We develop a technique to enable traffic forwarding between TSN and 5G communication technologies and demonstrate a proof-of-concept implementation of the proposed method using the NeSTiNG TSN network simulator, built on OMNeT++.

**RC3:** We develop and implement a novel TSN-5G gateway, and test its functionality on an actual TSN-5G network, addressing practical implications and diverse hardware limitations.

**RG3:** To design a framework to accurately map QoS requirements between TSN and 5G networks, ensuring consistent performance across the integrated system.

**RC4:** We develop a novel algorithm, called the QoS-MAN, to map QoS characteristics between TSN and 5G. The purpose of this algorithm is to facilitate the integration of traffic flows in a heterogeneous TSN-5G network.

**RG4:** To develop novel scheduling mechanisms for the allocation of 5G radio resources, ensuring the latency, and bandwidth needs of real-time TSN flows are met under varying network conditions.

**RC5:** We develop a robust flow-based radio resource scheduling approach to guarantee the uplink transmission of TSN traffic with stringent real-time requirements over 5G.

Figure 4.1: Mapping the included papers with the Research Goals and Thesis Contributions.

The research contributions are proposed in the form of published papers in conferences and journals. The order of the papers is in accordance with the contributions.

### 4.2.1 Paper A

**Title:** A Comprehensive Systematic Review of Integration of Time Sensitive Networking and 5G Communication

**Authors:** Zenepe Satka, Mohammad Ashjaei, Hossein Fotouhi, Masoud Daneshtalab, Mikael Sjödin, Saad Mubeen.

**Status:** Published in the Journal of Systems Architecture (JSA), Vol. 138, 2023.

**Abstract:** Many industrial real-time applications in various domains, e.g., automotive, industrial automation, industrial IoT, and industry 4.0, require ultra-low end-to-end network latency, often in the order of 10 milliseconds or less. The IEEE 802.1 time-sensitive networking (TSN) is a set of standards that supports the required low-latency wired communication with ultra-low jitter. The flexibility of such a wired connection can be increased if it is integrated with a mobile wireless network. The fifth generation of cellular networks (5G) is capable of supporting the required levels of network latency with the Ultra-Reliable Low Latency Communication (URLLC) service. To fully utilize the potential of these two technologies (TSN and 5G) in industrial applications, seamless integration of the TSN wired-based network with the 5G wireless-based network is needed. In this article, we provide a comprehensive and well-structured snapshot of the existing research on TSN-5G integration. In this regard, we present the planning, execution, and analysis results of the systematic review. We also identify the trends, technical characteristics, and potential gaps in the state of the art, thus highlighting future research directions in the integration of TSN and 5G communication technologies. We notice that 73% of the primary studies address the time synchronization in the integration of TSN and 5G technologies, introducing approaches with an accuracy starting from the levels of hundred nanoseconds to one microsecond.

Majority of primary studies aim at optimizing communication latency in their approach, which is a key quality attribute in automotive and industrial automation applications today.

**Authors' Contributions:** I was the main driver of the work under the supervision of the co-authors. The plan for the paper was formed in joint discussions with the co-authors. I performed the systematic literature review and wrote the draft of the paper. The co-authors have reviewed the paper, after which I have improved it.

### 4.2.2 Paper B

**Title:** Developing a Translation Technique for Converged TSN-5G Communication

**Authors:** Zenepe Satka, David Pantzar, Alexander Magnusson, Mohammad Ashjaei, Hossein Fotouhi, Masoud Daneshtalab, Mikael Sjödin, Saad Mubeen.

**Status:** Published in the 18th IEEE International Conference on Factory Communication Systems (WFCS), 2022.

**Abstract:** Time Sensitive Networking (TSN) is a set of IEEE standards based on switched Ethernet that aim at meeting high-bandwidth and low-latency requirements in wired communication. TSN implementations typically do not support integration of wireless networks, which limits their applicability to many industrial applications that need both wired and wireless communication. The development of 5G and its promised Ultra-Reliable and Low-Latency Communication (URLLC) integrated with TSN would offer a promising solution to meet the bandwidth, latency and reliability requirements in these industrial applications. In order to support such an integration, we propose a technique to translate the traffic between TSN and 5G communication technologies. As a proof of concept, we implement the translation technique in a well-known TSN simulator, namely NeSTiNg, that is based on the OMNeT++ tool. Furthermore, we evaluate the proposed technique using an automotive industrial use case.

**Authors' Contributions:** I was the main driver of the work under the supervision of the co-authors. David and Alexander helped with the implementation of my design in the simulator, while the other co-authors have reviewed the paper, after which I have improved it.

### 4.2.3 Paper C

**Title:** Enhancing Real-Time Networked Embedded Systems with End-to-end TSN-5G Network

**Authors:** Zenepe Satka, Mohammad Ashjaei, Didrik Nordin, Daniel Ragnarsson, Saad Mubeen

**Status:** Published in the 14th International Symposium on Industrial Embedded Systems (SIES), 2024. Invited to submit an extended version to the Journal of Systems Architecture (JSA), which is currently under review.

**Abstract:** This paper explores the integration of Time-Sensitive Networking (TSN) with 5G cellular networks to support high-bandwidth and low-latency end-to-end communication in networked embedded systems. Integrating TSN with 5G has the potential to support predictable and deterministic end-to-end communication, as well as to significantly enhance scalability, particularly in industrial automation, by providing flexibility, efficiency, and responsiveness. To ensure smooth integration while preserving TSN's Quality of Service (QoS) requirements, effective traffic translation, and time synchronization within the network are crucial. Time synchronization is a cornerstone for time-sensitive application, ensuring precise coordination across devices and enabling deterministic communication. In this regard, this paper addresses key challenges related to traffic translation, QoS implementation, latency and synchronization in both TSN and private 5G networks, analyzed through a realistic scenario. Understanding these metrics is essential for devising effective integration strategies. Our findings indicate that it is possible to achieve latencies under 20 ms in an integrated TSN-5G network, given our specific configuration of a private

5G setup with a channel bandwidth of 40 MHz. We also identify the need for the implementation of a proper QoS mechanism to enable the prioritization of high-critical data transmission, and show the impact of different QoS profile configuration on the end-to-end latencies.

**Authors' Contributions:** I am the main driver of the work under the supervision of co-authors Saad and Mohammad. I have developed the design of the gateway, while the other co-authors contributed towards the implementation of the use case in realistic hardware.

### 4.2.4 Paper D

**Title:** QoS-MAN: A Novel QoS Mapping Algorithm for TSN-5G Flows

**Authors:** Zenepe Satka, Mohammad Ashjaei, Hossein Fotouhi, Masoud Daneshtalab, Mikael Sjödin, Saad Mubeen.

**Status:** Published in the 28th IEEE International Conference on Embedded and Real-Time Computing Systems and Applications (RTCSA), 2022.

**Abstract:** Integrating wired Ethernet networks, such as Time-Sensitive Networks (TSN), to 5G cellular network requires a flow management technique to efficiently map TSN traffic to 5G Quality-of-Service (QoS) flows. The 3GPP Release 16 provides a set of predefined QoS characteristics, such as priority level, packet delay budget, and maximum data burst volume, which can be used for the 5G QoS flows. Within this context, mapping TSN traffic flows to 5G QoS flows in an integrated TSN-5G network is of paramount importance as the mapping can significantly impact on the end-to-end QoS in the integrated network. In this paper, we present a novel and efficient mapping algorithm to map different TSN traffic flows to 5G QoS flows. To the best of our knowledge, this is the first QoS-aware mapping algorithm to exchange flows between TSN and 5G network domains. We evaluate the proposed mapping algorithm on synthetic scenarios with random sets of constraints on deadline, jitter, bandwidth, and packet loss rate. The evaluation results show that the proposed mapping algorithm can fulfill over 90% of the applications' constraints.

**Authors' Contributions:** I was the main driver of the work under the supervision of the co-authors. The plan for the paper was formed in joint discussions with the co-authors. I developed the QoS-MAN algorithm and wrote the draft of the paper. The co-authors have reviewed the paper, after which I have improved it.

### 4.2.5 Paper E

**Title:** Real-time Scheduling of 5G Radio Resources to Support Time Sensitive Networking Traffic

**Authors:** Zenepe Satka, Federico Aromolo, Mohammad Ashjaei, Alessandro Biondi, Daniel Casini, Hossein Fotouhi, Niccolo Borgioli, Masoud Daneshtalab, Mikael Sjödin, Saad Mubeen

**Status:** Published as MRTC technical report, ISRN MDH-MRTC-355/2025-1-SE, Mälardalen University, 2025.

**Abstract:** Recent advancements in cyber-physical systems (CPS) are enabling numerous new applications and industrial use cases that require high bandwidth, low-latency, low-jitter, and timing-predictable communication, integrating both wired and wireless communication technologies. To meet these requirements the Time-Sensitive Networking (TSN) standards are emerging for wired communication, while the fifth generation of cellular networks (5G) stands out as a strong candidate for the wireless communication. However, the integration of TSN with 5G introduces new challenges regarding the scheduling of 5G radio resources to various TSN flows due to the dynamic channel fluctuations of wireless communication. In this paper, we propose a robust flow-based radio resource scheduling approach to guarantee the uplink transmission of TSN traffic with stringent real-time requirements. We propose a two-phase 5G radio resource scheduling approach for the transmission of TSN traffic, guaranteeing the hard real-time requirements of ST traffic, while scheduling AVB traffic with soft timing requirements. We evaluate the performance of our approach by running a series of experiments under various traffic loads, demonstrating its scalability, feasibility, and overall effectiveness.

**Authors' Contributions:** I am the main driver of the work under the supervision of Saad, Mohammad, Masoud, Mikael and Hossein. I formulated the problem and wrote the draft of the paper. The second co-author helped with the implementation of the problem in CPLEX. The other co-authors have reviewed the paper, after which I have improved it.

# Chapter 5

# Conclusion and Future Directions

In this chapter, we conclude with presenting a summary of our findings, as well as outlining some potential directions for future research.

## 5.1 Summary and Conclusions

In this thesis, we introduce novel techniques and mechanisms to support the end-to-end communication over integrated TSN-5G networks for real-time applications. One of the main contributions of this thesis is the comprehensive and well-structured snapshot of the existing research on TSN-5G integration using a fully-concentrated and well-organized classification scheme. This detailed investigation is presented in a comprehensive systematic literature review which will help both the researchers and the practitioners in identifying and understanding the existing solutions and their applicability in the industrial environments. Moreover, it helps in the identification of gaps in the current research and highlighting the opportunities for further research in the area of TSN-5G integration.

Considering the identified gaps in the research area, we first focus on the design and evaluation of TSN-5G architectures on an actual hardware, handling fundamental disparities among TSN's Ethernet-based communication and 5G's cellular technology. To ensure compatibility within TSN-5G network, we develop and implement a gateway that serves as an interface to guarantee effective traffic forwarding among the networks. The gateway incorporates two main functionalities. First, it translates flows from the TSN communication protocol format into the IP packets to ensure seamless interoperability among the networks. We present a proof-of-concept implementation of the proposed technique in a commonly used TSN network simulator NeSTiNG that is based on OMNeT++. Moreover, we implemented the gateway on a private TSN-5G setup, where we could also configure different 5G QoS profiles to ensure the stringent latency requirements of high-critical traffic when co-existing with less-critical traffic. Our findings showed that we can effectively operate remote control of a vehicle through the integrated TSN-5G network achieving the required latency, even in scenarios where multiple devices are connected to the private 5G network.

In addition, we delve into the QoS configuration and mapping strategies to handle the end-to-end QoS requirements of real-time applications over TSN-5G networks. To ensure the applications' requirements across the entire network, it is important to interpret the TSN traffic requirements to the 5G radio resource types and proper standardized 5G QoS profiles. We introduce a novel and efficient mapping algorithm which maps different TSN traffic flows to 5G QoS flows. The algorithm uses the application requirements such as deadline, jitter, bandwidth and packet loss rate to map the TSN traffic flow to a specific 5G QoS profile that fulfill the needs. The proposed algorithm, called the QoS-MAN, could systematically and efficiently map any Ethernet traffic flows to 5G QoS flows.

Furthermore, to address the challenge of scheduling 5G radio resources to TSN flows while ensuring the requested deterministic communication, we design a novel flow-based radio resource scheduling mechanism that allocates 5G radio resources for the transmission of TSN-specific flows with stringent real-time requirements over 5G. Our scheduling mechanism consists of two phases. Phase 1 handles the offline scheduling of periodic ST flows with stringent timing constraints on the transmission and a fixed data rate requirement, and Phase 2 consists of the semi-online schedule of the AVB flows with QoS requirements considering the 5G channel fluctuations at runtime, which have an impact on the data transmission's reliability and capacity. To properly utilize the 5G radio resources, we optimize the allocation of radio resources in the time and frequency domain, while guaranteeing the requested QoS-es to TSN flows. Moreover, we propose a set of heuristics to enhance the scalability of our optimization algorithm.

In summary, we have designed and implemented the necessary means to support the end-to-end real-time communication across TSN-5G networks, presenting proof-of-concept implementations in both simulation and actual TSN-5G setup.

## 5.2 Future Work

Overall, the integration of TSN and 5G can have significant implications for various industries. It can lead to new possibilities for real-time control in industrial systems, and can enable new applications and services. The full capabilities and potential of each are yet to be fully realized, and there are ongoing efforts to further improve and enhance the technologies to be compatible with existing networks and devices.

However, several research directions remain for the future work:

1. **An end-to-end time synchronization approach:** The establishment of an end-to-end time synchronization is required to support the transmission of time-sensitive data across integrated TSN-5G networks. The Precision Time Protocol (PTP), defined by the IEEE 1588 standard [54], is a network protocol designed to achieve sub-microsecond level of accuracy. It decides a grandmaster clock in the network which distributes time information to other devices, so called slaves, and synchronizes clock slaves to the grandmaster clock. In addition, IEEE 802.1AS [55] defines the generalized PTP (gPTP) specifically tailored for time-sensitive networking, which extends the IEEE 1588 PTP standard to provide high-precision clock synchronization in Ethernet-based networks. The 3GPP Release 18 [10] utilizes PTP to enable time synchronization between TSN and 5G, making it possible to control a deterministic time synchronization in network-based applications. However, implementing PTP di-

rectly across the TSN and 5G networks is challenging due to the differences in their architectures, and also the hardware limitations. Although several research articles investigate the clock synchronization among TNS-5G systems [56, 57], it is still challenging to prevent drifting between the clocks at the ingress and egress of the 5G system, or between the clocks of the UE and the gNB when focusing on the wireless link [15]. Therefore, further research is needed to optimize the accuracy of the reference clock send from the gNB at the air interface.

2. **Mechanisms to ensure reliability in integrated TSN-5G networks:** Reliability is one of the key parameters for the transmission of high critical TSN flows over 5G, therefore it is important to be considered as one of the main research directions. To ensure high reliability, there is a need for path redundancy mechanisms to reduce packet loss rate in the network. TSN has established several methods both in the standards and in the research compared to 5G, and the integration of such mechanisms across TSN and 5G remains a subject to further exploration. The URLLC supported in 5G contributes to the support for the high reliability guarantees on the 5G network by establishing two PDU sessions for the same UE using the New Radio Dual Connectivity technology [58]. However, the research is still in the theoretical stage, therefore there is a need to contribute towards the development and evaluation of the reliability and retransmission mechanisms on the air interface in the future.

3. **Managing and orchestrating the 5G network slices:** Network Slicing stands out as a promising technique to enhance bandwidth utilization over 5G networks, considering the exponential growth of mobile users and IIoT devices. This technology splits a single network infrastructure into multiple virtualized networks to enable elastic resource scaling and fulfill diverse requirements requested by a particular application [59]. We can create different networks slices for the TSN traffic flows based on their transmission requirements. However, the research area is still missing a unified framework for managing and orchestrating the network slices in 5G networks covering a wide range of applications.

4. **End-to-end scheduling of resources in TSN and 5G network:** The

end-to-end scheduling of 5G radio resources for the transmission of TSN flows which are sensitive to dynamic nature of 5G wireless links remains a complex challenge. This theses presented an uplink flow-based scheduling approach for integrated TSN-5G networks, however the downlink transmission of TSN flows over 5G is not trivial and requires efforts for yet another solution. There is a need for an end-to-end scheduling of the TSN-5G network ensuring both the uplink and downlink transmission of TSN flows with stringent timing requirements. In addition, it is also important for the TSN network to calculate and handle jitter implied from the 5G system in order to properly calculate the final schedule of flows using traffic shapers and the GCL.

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