Mälardalen University Press Licentiate Theses
No. 337

# END-TO-END QOS MAPPING AND TRAFFIC FORWARDING IN CONVERGED TSN-5G NETWORKS

**Zenepe Satka**

**2023**

Mälardalen University

School of Innovation, Design and Engineering

ISBN 978-91-7485-587-6
ISSN 1651-9256
Printed by E-Print AB, Stockholm, Sweden

*"To my dad,* ***Petrit Satka****,*
*my hero and lifelong champion,*
*who always encouraged me to*
*fly towards my dreams."*

# Acknowledgement

I take the opportunity to express my gratitude to my great team of supervisors: Saad Mubeen, Mohammad Ashjaei, Masoud Daneshtalab, Hossein Fotouhi, and Mikael Sjödin, for bringing the weight of their considerable experience and knowledge to the project. Thank you all for the invaluable guidance and constructive feedback. I enjoyed every moment of our discussions, trips, and meetings.

I would like to express a deep sense of gratitude to my main supervisor, Saad Mubeen, for his persistent help and constant encouragement throughout my studies. I learned from his positive attitude that it is better to be a leader than a boss, always encouraging me to do my best, and always being there to guide and support, no matter when.

Next, I would like to thank Mohammad Ashjaei, who has been guiding me since my master's thesis. He taught me how to think positively in every situation and that it is always possible to write a great paper in two days.

In addition, 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.

I would like to acknowledge my friends and colleagues at MDU. I enjoyed every activity we did together, including the Fikas, after-work parties, and hackathons. Special thanks to the head of the Division of Networked and Embedded Systems (IDT), Svetlana Girs, for creating a happy work environment since the very first day at MDU.

In addition, I would like to thank my family - my parents and brother - for their endless support and love. Thank you, Mom, for always believing in me and encouraging me to work hard and never give up. Thank you, Dad, for all the immense sacrifices made throughout the years. Without your colossal efforts, I wouldn't be where I am now.

Last but not least, I am eternally grateful to my better half, Jelio. Thank you for being there for me for the past ten years as a friend, a partner, and an adviser, especially during the tough times.

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

Zenepe Satka
February, 2023,
Västerås, Sweden.

# Abstract

The advancement of technology has led to an increase in the demand for ultra-low end-to-end network latency in real-time applications with a target of below 10 ms. 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 for real-time applications. TSN is designed for fixed networks thus it misses the flexibility of wireless networks. To overcome this limitation and to increase its applicability in different applications, an integration of TSN with other wireless technologies is needed. The fifth generation of cellular networks (5G) supports real-time applications with its Ultra-Reliable Low Latency Communication (URLLC) service. 5G URLLC is designed to meet the stringent timing requirements of these applications, such as 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 contemporary and future industrial applications. However, to achieve the end-to-end Quality of Service (QoS) requirements of a TSN-5G network, a significant effort is required due to the large dissimilarity between these technologies.

This thesis presents a comprehensive and well-structured snapshot of the existing research on TSN-5G integration that identifies gaps in the current research and highlights the opportunities for further research in the area of TSN-5G integration. In particular, the thesis identifies that the state of the art lacks an end-to-end mapping of QoS requirements and traffic forwarding mechanisms for a converged TSN-5G network. This lack of knowledge and tool support hampers the utilisation of ground-breaking technologies like TSN and 5G. Hence, the thesis develops novel techniques to support the end-to-end QoS mapping and traffic forwarding of a converged TSN-5G network for predictable communication. Furthermore, the thesis presents a translation technique between TSN and 5G with a proof-of-concept implementation in a well-known TSN network simulator. Moreover, a novel QoS mapping algorithm is proposed to support the systematic mapping of QoS characteristics and integration of traffic flows in a converged TSN-5G network.

# Sammanfattning

Teknikens framsteg har lett till en ökning av efterfrågan på ultralåg end-to-end nätverkslatens i realtidsapplikationer med ett mål på under 10 ms. IEEE 802.1 Time-Sensitive Networking (TSN) är en uppsättning standarder som stöder den trådbundna kommunikationen med låg latens och ultralågt jitter för realtidsapplikationer. TSN är designad för fasta nätverk och missar därför flexibiliteten hos trådlösa nätverk. För att övervinna denna begränsning och för att öka dess tillämpbarhet i olika applikationer behövs en integration av TSN med andra trådlösa teknologier. Den femte generationen av cellulära nätverk (5G) stöder realtidsapplikationer med sin Ultra-Reliable Low Latency Communication (URLLC)-tjänst. 5G URLLC är designad för att möta de stränga tidskraven för dessa applikationer, som att tillhandahålla pålitlig kommunikation med latenser så låga som 1 ms. Sömlös integrering av TSN och 5G behövs för att fullt ut utnyttja potentialen hos dessa teknologier i samtida och framtida industriella tillämpningar. Men för att uppnå end-to-end QoS-kraven för ett TSN-5G-nätverk krävs en betydande ansträngning på grund av den stora olikheten mellan dessa teknologier. Denna avhandling presenterar en omfattande och välstrukturerad ögonblicksbild av den befintliga forskningen om TSN-5G-integration som identifierar luckor i den aktuella forskningen och belyser möjligheterna för ytterligare forskning inom området TSN-5G-integration. Speciellt identifierar avhandlingen att den senaste tekniken saknar en end-to-end-mappning av QoS-krav och mekanismer för vidarebefordran av trafik för ett konvergerat TSN-5G-nätverk. Denna brist på kunskap och verktygsstöd hindrar användningen av banbrytande teknologier som TSN och 5G. Därför utvecklar avhandlingen nya tekniker för att stödja end-to-end QoS-kartläggning och trafikbefordran av ett konvergerat TSN-5G-nätverk för förutsägbar kommunikation. Vidare presenterar avhandlingen en översättningsteknik mellan TSN och 5G med en proof-of-concept-implementering i en välkänd TSN-nätsimulator. Dessutom föreslås en ny QoS-mappningsalgoritm för att stödja systematisk kartläggning av QoS-egenskaper och integration av trafikflöden i ett konvergerat TSN-5G-nätverk.

# 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), 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 18th IEEE International Conference on Factory Communication Systems (WFCS), 2022.

**Paper C:** 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 28th IEEE International Conference on Embedded and Real-Time Computing Systems and Applications (RTCSA), 2022.

**Paper D:** Zenepe Satka, Inés Álvarez, Mohammad Ashjaei, Saad Mubeen. *Work in progress - A centralized configuration model for TSN-5G networks.* In the 27th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), 2022.

---

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

# Contents

# Acronyms

**3GPP** 3rd Generation Partnership Project. 2, 3, 12–14, 20

**5G** Fifth Generation of Mobile Networks. 1–4, 12–21, 27, 28

**AF** Application Function. 17, 18

**AMF** Access and Mobility Management Function. 17

**AVB** Audio-Video Bridging. 7–9

**BE** Best Effort. 8, 9

**CBS** Credit-based Shaper. 8, 9

**CNC** Centralized Network Configuration. 10, 11, 18

**CP** Control Plane. 17, 18

**CUC** Centralized User Configuration. 10

**DL** Downlink. 13–15

**DRB** Data Radio Bearers. 16

**DS-TT** Device-side TSN Translator. 16, 18

**eMBB** enhanced Mobile Broadband. 2, 13

**GBR** Guaranteed Bit Rate. 13, 14

**GCL** Gate Control List. 8, 10

**gNB** next generation NodeB. 17, 18

**IIoT** Industrial Internet of Things. 1, 2

**IoT** Internet of Things. 2, 13

**LAN** Local Area Networks. 7

**LLC** Logical Link Control. 7

**LTE** Long-Term Evolution. 12, 13

**MAC** Media Access Control. 7, 14, 17

**MAN** Metropolitan Area Networks. 7

**MDBV** Maximum Data Burst Volume. 18

**NEF** Network Exposure Function. 17

**NIC** Network Interface Card. 7

**Non-GBR** Non-Guranteed Bit Rate. 13, 14

**NW-TT** Network-side TSN Translator. 16, 18

**PCF** Policy Control Function. 17, 18

**PCP** Priority Code Point. 8, 14

**PDB** Packet Delay Budget. 18

**PDR** Packet Detection Rule. 14, 15

**PDU** Packet Data Unit. 13, 14, 17

**PER** Packet Error Rate. 18

**QFI** QoS Flow Identifier. 14, 15

**QoS** Quality of Service. 3, 8–10, 13–18, 20, 27, 28

**RAN** Radio Access Network. 13, 16, 18

**SDAP** Service Data Adaptation Protocol. 15

**SDF** Service Data Flow. 15

**SMF** Session Management Function. 15, 17

**ST** Scheduled Traffic. 8

**TAS** Time-Aware Shaper. 8, 10

**TDMA** Time Division Multiple Access. 7

**TSN** Time-Sensitive Networking. 1–4, 7–12, 14, 16–21, 27, 28

**TT** TSN Translator. 17, 18

**UDM** Unified Data Management. 17

**UE** User Equipment. 13–16, 18

**UL** Uplink. 13–15

**ULL** ultra-low latency. 1

**UP** User Plane. 16–18

**UPF** User Plane Function. 13–15, 17, 18

**URLLC** Ultra-Reliable Low-Latency Communication. 2, 13

**WAN** Wide Area Networks. 7

# Glossary

**bridges** Also referred as switches, are network devices responsible for forwarding data packets between network segments based on their physical addresses. 8–11

**end station** Also referred as node, is a device or application that generates or consumes data packets in a wired or wireless network. 7, 10

**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. 1, 3, 13, 21, 23, 27

**flow** Refers to data packets or messages that are transmitted between two end stations over a network. 8–11, 13–16, 18

**interoperability** Is the ability of different networks or systems to communicate easily without the need for additional tools or interfaces. 11

**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. 1–3, 7, 9, 14, 21, 27, 28

**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. 1–3, 7, 8, 13

**User Equipment** refers to end-user devices or end stations that are used to access a wireless network, such as 5G. 13, 18

# Part I

# Thesis

# Chapter 1

# Introduction

There is an urgent need for future industrial networks for ultra-reliable and deterministic communication in order to involve their fast and precise processes [1]. The physical infrastructure in smart factories will require communication technologies that could deliver critical control, while providing automation services. Furthermore, Industrial IoT (IIoT) applications like autonomous driving, robotics, as well as augmented and virtual reality, may require high data rates and ultra-low latency (ULL) [2, 3]. These applications often require end-to-end latency in the range of microseconds [4]. Therefore, a dedicated mechanism is needed to address low-latency requirement of ULL applications.

Time-Sensitive Networking (TSN) is a set of standards for Ethernet-based communication[1] that fulfills the requirements of real-time applications with ultra low jitter [5,6]. Since it is a wired network, it uses onboard connection to achieve the determinism and reliability of the network. The onboard connection is actually a constraint for future industrial applications. Wired connection limits the movement of the vehicles and it also limits the connection only in the areas where wired connection is feasible. The flexibility of a mobile connection is a missing feature of TSN. To overcome this limitation, the integration of TSN with wireless technologies is compulsory for contemporary and future industrial applications.

The early generations of mobile networks have not been designed to achieve low-latency and reliability. They address the consumer communications with asymmetric data, and thus the communication is missing the built-in flexibility required by industrial applications. The fifth generation of mobile networks (5G) [7, 8] can provide the flexibility

---

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

and scalability required of the mentioned applications. 5G supports real-time applications by using a service called Ultra-Reliable Low Latency Communication (URLLC), which is part of the 3rd Generation Partnership Project (3GPP) Releases [9, 10]. URLLC is a promising candidate for real-time wireless communication to support latency of 1 ms and reliability of 99.999% [11]. Enhanced mobile broadband (eMBB) and massive machine type communication [12] are two other services of 5G provided by 3GPP that can be useful for industrial Internet of Things (IIoT) use cases [13].

A converged wired and wireless network integrating TSN and 5G is needed to achieve real-time requirements, determinism as well as mobility and scalability of communication in contemporary and future industrial applications. In order to achieve such a converged network, a significant effort is required due to very different techniques and protocols used on a wired and wireless network. An application of the converged TSN-5G network (i.e., TSN within vehicles and 5G among the vehicles and their control centre) is shown in Figure. 1.1. In this automotive use-case there is an urgent need for high-bandwidth and low-latency predictable communication both within each vehicle and among the vehicles and their remote control centre.

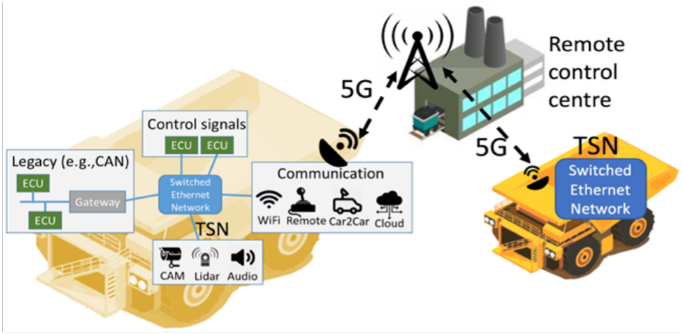


**Figure 1.1:** Envisioned conceptual view of collaborating vehicles utilizing converged TSN-5G networks (PROVIDENT [2]).

> Our vision is that a converged TSN-5G network is a viable solution to provide a seamless and flexible communication infrastructure which meets the real-time requirements of holistic network communication in collaborating connected vehicles and other domains; such as industrial automation, industry 4.0 and industrial IoT.

---

[2] PROVIDENT is the name of our research project meaning "Predictable Software Development in Connected Vehicles Utilising Blended TSN-5G Networks" Link to PROVIDENT.

## 1.1 Motivation and Research Challenges

Besides all the benefits of integrating TSN and 5G technologies, several core challenges need to be addressed. Some notable challenges include (i) understanding the different architectural trade-offs in a joint TSN-5G architecture, (ii) time synchronization, (iii) handling end-to-end QoS requirements between TSN and 5G, and (iv) simulation and implementation of a TSN-5G network in a real-world environment, among others. Although the interaction of both systems is part of 3GPP specifications, there are still gaps for future investigation on this interaction since there are different approaches and aspects, which are still unclear to the research community and industries.

To achieve the end-to-end QoS requirements and traffic forwarding between TSN and 5G, a significant effort is required due to the large dissimilarity of the considered systems. Both TSN and 5G use different techniques and protocols to forward traffic from one user to another, to classify and prioritize the traffic, as well as to allocate resources such as bandwidth, to each class of traffic by ensuring that the QoS requirements are met. In this thesis, we aim at addressing the handling of QoS requirements between TSN and 5G which is essential for ensuring that real-time and critical data are transmitted with the necessary level of reliability, determinism, and predictable low-latencies.

### 1.1.1 Research Goal

In this section, we specify the research goal of this thesis which targets resource management and traffic forwarding in converged TSN-5G networks. The purpose of this thesis is to provide solutions and techniques to achieve the research goal (RG) defined as follows:

> **Research Goal (RG):** *Developing new techniques to provide an end-to-end QoS mapping and traffic forwarding of a converged TSN-5G network for predictable communication.*

The main RG can be refined into three sub-goals ($SG_i$) as follows:

- $SG_1$: To identify challenges and opportunities in the current state-of-the-art on the integration of TSN and 5G networks.

- $SG_2$: To efficiently translate the traffic and map QoS requirements between TSN and 5G network domains.

- $SG_3$: To design a centralized architecture to configure the TSN-5G network, and forward traffic from TSN to 5G and vice-versa.

## 1.2 Research Process

To address the research goal presented earlier in Section 1.1.1, this work uses the hypothetico-deductive [14] research method for computer science. It also considers investigating the research area and designing 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. The research process is presented in Figure 1.2.

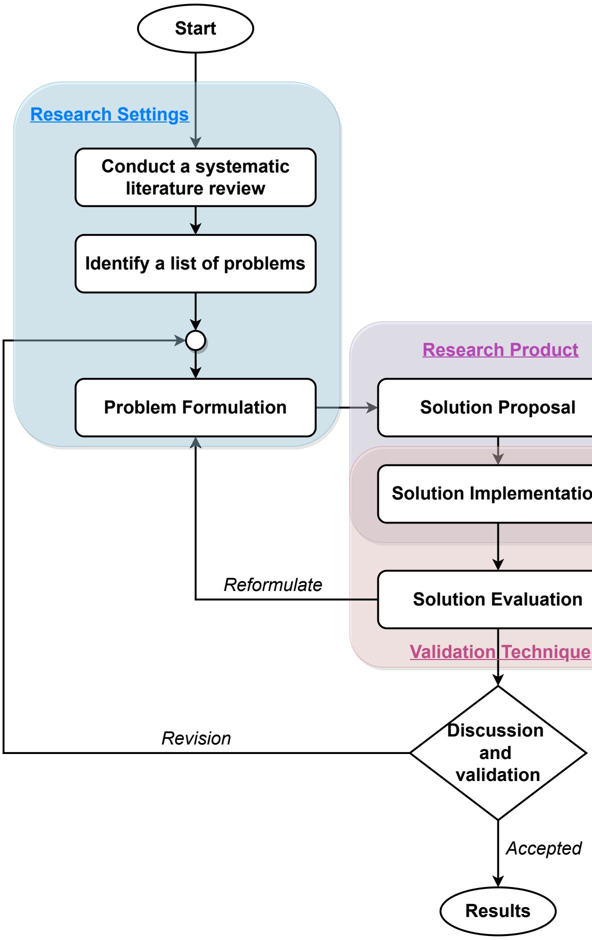


**Figure 1.2:** Research process.

The research process consists of the following steps:

1. **Systematic Literature Review:** A systematic literature review (SLR) [15] 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 reusability 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[3], and Arcticus Systems[4].
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.

---

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

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

# Chapter 2

# Background and Related Work

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

## 2.1 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 link 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 [16]. This set of extensions fulfil the stringent real-time requirements, but they require modifications to the IEEE Ethernet MAC [17]. Therefore, the Audio-Video Bridging (AVB) working group broadened in scope [18] 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.

## 2.2 Time-Sensitive Networking

TSN is a set of standards that enable the reliable and deterministic delivery 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 [19, 20]. 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.

### 2.2.1 Traffic Forwarding and Traffic Classes in TSN

TSN switches (or bridges) 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. TSN switches use the PCP value to classify incoming frames into different priority levels and apply the necessary (QoS) mechanisms, such as traffic shaping, prioritization, and reservation, to ensure that time-sensitive data is delivered with the required accuracy and reliability. There are two scheduling mechanisms available in TSN: (i) Credit-based shaper (CBS) for AVB, and (ii) Time-Aware Shaper (TAS), 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 with Class A and Class B, and (3) BE traffic, presented in Figure 2.1. 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 TAS mechanism controlled by the GCL [21]. 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 priority classes, class A and B, with A as the highest priority queue. The AVB traffic queues are controlled by the CBS mechanism [22]. 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.

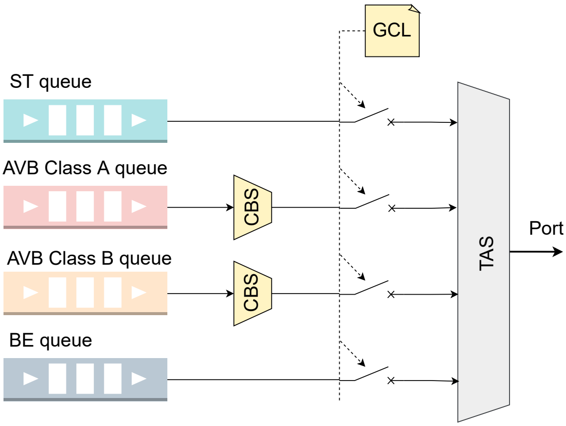


**Figure 2.1:** Traffic forwarding in a TSN egress port.

### 2.2.2 TSN configuration models

The IEEE 802.1Qcc [23] provides a framework for building TSN networks. According to the 802.1Qcc standard there exist different configuration models to manage the behavior of TSN bridges as presented below. The choice of configuration model depends on the requirements of the application and the network architecture.

**Fully distributed model:** In the fully distributed model, each network component (end devices, or TSN bridges) shares its properties required to establish a TSN flow with all other components that are part of the flow in order to establish a TSN QoS. The end devices send their requirements to the TSN bridges, which then propagates the requirements along the TSN stream. Each end station in the fully centralized model handles its own resource management. A visual representation of the TSN fully distributed configuration model is presented in Figure 2.2.

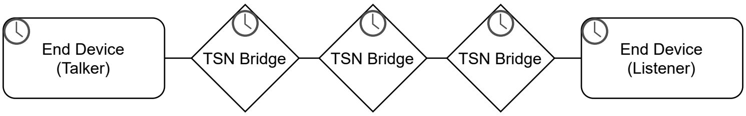


**Figure 2.2:** Fully Distributed TSN Configuration Model.

**Centralized network/distributed user model:** In the centralized network/distributed user model, a Centralized Network Configuration (CNC) entity is added as shown in Figure 2.3. TSN bridges send their capabilities and requirements to the CNC, while the end devices still send their properties among each other. The CNC facilitates more complex TSN features, such as TAS and preemption of flows. It defines the traffic classes, scheduling mechanisms, and GCLs for each TSN bridge, and provides these configurations to the bridges over the network.

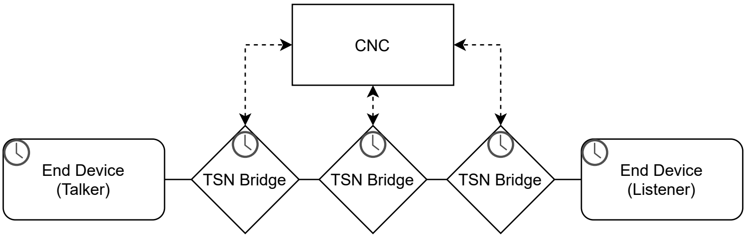


**Figure 2.3:** Centralized / Distributed TSN Configuration Model.

**Fully centralized model:** The fully centralized model includes two centralized entities. First, the end devices send their requirements to an entity named Centralized User Configuration (CUC). Second, the CNC gets the complete picture of the network by receiving the bridge capabilities and topology, and end stations' requirements from the CUC. A visual representation of the fully centralized configuration model is shown in Figure 2.4.

For a better understanding of this model we present the flow of information as follows:

1. The end devices send to the CUC their QoS requirements, such as data rate, traffic class, priorities and worst-case latency.

2. The CUC relays the end devices' requirements to the CNC.

3. The TSN bridges send their capabilities to the CNC. These capabilities include bridge delays per port and class, propagation delays per port, and priorities.

4. Since CNC has an overview of the whole network, it calculates a schedule for the network with regards to starting times of flows and the opening and closing timings of the gate control within each of the TSN bridges.

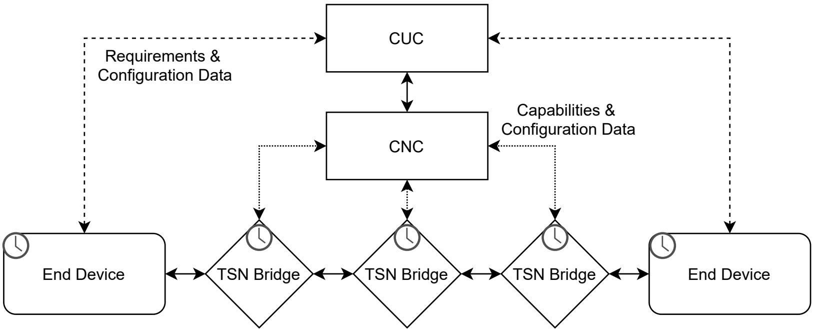


**Figure 2.4:** Fully Centralized TSN Configuration Model. The clocks in each of the end devices and TSN bridges indicate that the components are time synchronized as per IEEE 802.1AS.

### 2.2.3 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. interoperability is an important challenge for TSN. 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, TSN as a wired technology, is limited in the areas where a cable connection is feasible, though missing the flexibility of mobile connection. This can limit the applicability of TSN in scenarios where mobility is required such as autonomous vehicles or industrial drones.

## 2.3 Evolution of mobile networks

The evolution of mobile networks starts with the First generation (1G) technology, which was launched in 1980's, introducing wireless voice data. Then the evolution of mobile networks continues with 2G, 3G, 4G, and 5G in order to improve user experience with communication systems [24] as shown in Figure 2.5.

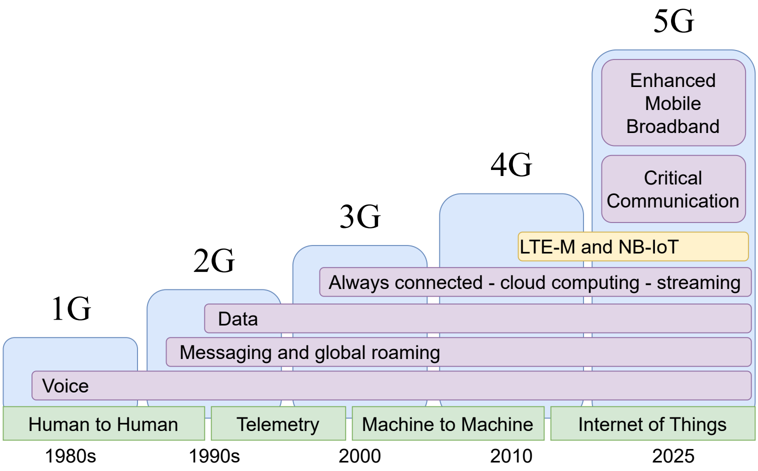


**Figure 2.5:** Evolution of mobile technology from 1G to 5G[1].

The deployment of fifth generation of mobile communications (5G) is standardized into two phases [25]. *5G Phase 1* was introduced by 3GPP Release 15 [26], 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 Phase 2* was explored by 3GPP Release 16 [9], introducing a new core network named Next Generation Core Network (NGCN) to support advance functions such as network slicing [27].

---

[1] https://iot.telenor.com/technologies/evolution-mobile-technology/

## 2.4 5G Network

5G network [28,29] provides significant improvements to the Long Term Evolution (LTE) technology. 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-type communications (mMTC), and ultra-reliable low-latency communication (URLLC), [30–32]. 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 Release 17. With URLLC features, the new 5G Radio Access Network (RAN) [33] can achieve ultra-low latency down to 1 ms and reliability up to 99.9999%. Within the core network, latency is typically below 1 ms [34]. The desired QoS requirements for URLLC depend on the applications as shown in Table 2.1.

**Table 2.1:** Expected QoS requirements for URLLC [32,35].

| **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 |

### 2.4.1 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 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 Radio Area Network (RAN) to the Internet.

A 5G QoS flow is assigned to every flow or packet 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 quality of service (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 [36]. 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.

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 [37]. 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.

### 2.4.2 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 2.6 describes the process of packet filtering inside 5G. The data packets from the applications arrives 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.

The 3GPP Release 16 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 [9].

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 [9]. 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

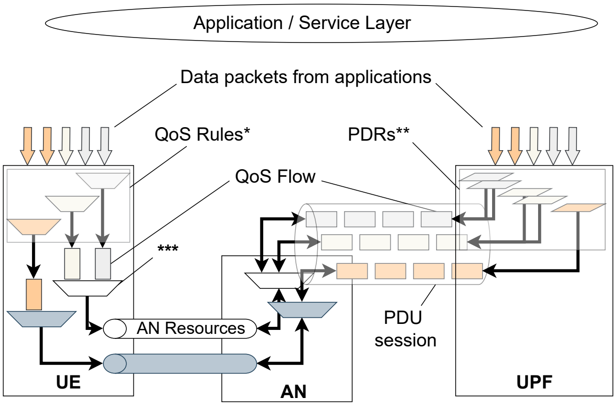


**Figure 2.6:** Packet classification, user plane marking and mapping to radio resources [37].

.

- 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

should be assigned to every application flow.

### 2.4.3 QoS Identifier Insertion

Considering the DL direction[2], 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 2.7. 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).

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 QoSes. 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

---

[2] For the sake of simplicity from now on, we only consider DL direction, as UL works in a similar way.

QoS flows to Data Radio Bearers (DRB). However, this type of mapping is beyond the scope of this work.

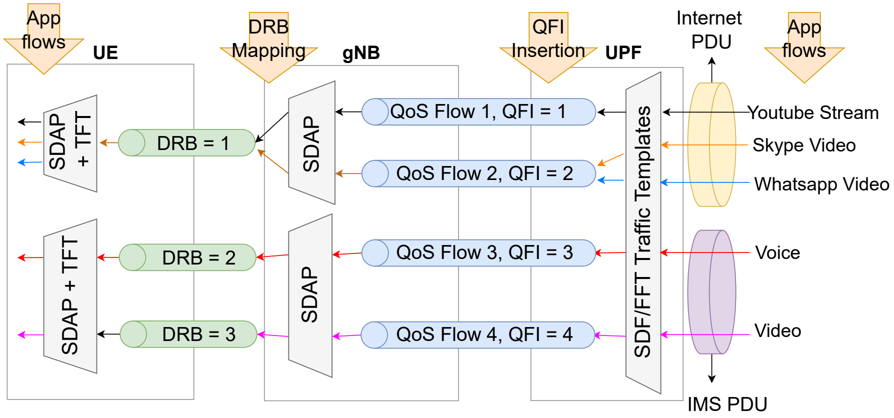


**Figure 2.7:** Example of QoS realization for downlink packets. Source: Rodini 2017, slide 6 [38].

## 2.5 5G as a Logical/Transparent TSN Bridge

Integration of 5G into TSN is based on either having 5G with the capabilities of TSN or integrating 5G as a logical TSN bridge. In the first approach, 5G is seen as a cable link between the devices [39], while in the second approach, 5G is seen as a black-box TSN bridge. 5G as a logical TSN bridge approach is the most focused in the existing works [40, 41].

The core architecture for TSN-5G design where 5G appears as a logical TSN bridge is presented in Figure 2.8. In this architecture 5G appears a black-box to the TSN network. It introduces two TSN translators to provide seamless communication between TSN and non-TSN devices (5G devices). The TSN translators are established on the device-side (DS-TT) and the network-side (NW-TT) of the logical TSN bridge as shown in Figure 2.8. From the user plane's (UP) perspective, the logical TSN Bridge is a virtual tunnel between the UE and the TSN Network. The DS-TT translates the necessary parameters of TSN to 5G QoS to establish the message's priority on the device-side. This is transmitted from the RAN to the network-side, which holds the TSN network. The NW-TT handles the translation from the 5G QoS to TSN QoS so that the frame maintains correct priority within the integrated network [9]. The introduction of the TSN translators at the device-side and network-side makes it possible to reuse many of the existing interfaces defined for the 5G systems.

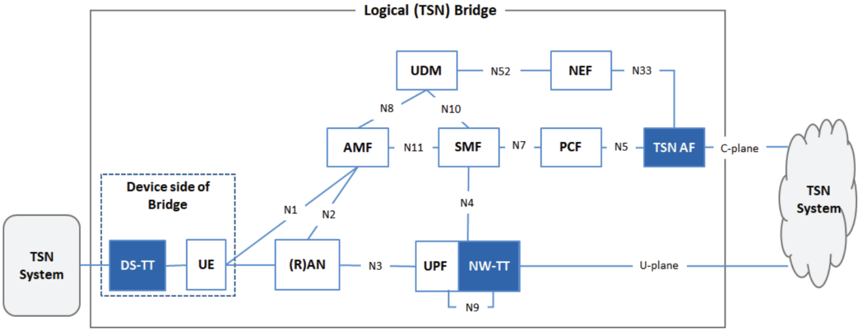


**Figure 2.8:** 5G as a logical TSN bridge [9].

The following concepts are a part of the core architecture for a TSN-5G design presented also in Figure 2.8; 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 [42].

- 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 and 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 AF via the PCF, giving the MAC addresses of the TT 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 AF, and maps the TSN QoS parameters to a 5QI. The 5QI is a scalar reference to certain 5G QoS characteristics, such as priority, Package Delay Budget (PDB), Package Error Rate (PER) and Max data burst volume (MDBV).

- Application Function (AF): Communicates with the CNC, 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 UP 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 [43].
- 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.
- RAN: A 5G capable device which acts as the access point for the wireless side of the logical TSN bridge, sometimes also known as new Generation Node B (gNB). It communicates with one or many UE.

# Chapter 3

# Thesis contributions

In this chapter, we present a summary of the contributions to realize the defined goal of this thesis along with a mapping of each contributions towards the subgoals of this thesis.

## 3.1 Technical Contributions

In this section, we present a summary of the research contributions of this thesis.

### 3.1.1 Contribution 1: Providing a comprehensive and well-structured snapshot of the existing research on TSN-5G integration

The first research contribution ($C_1$) in this thesis is to provide a detailed investigation of state of the art on TSN-5G integration and provide a fully-concentrated and well-organized classification scheme of the relevant publications. This will help the researchers and practitioners in identifying and understanding the existing solutions and their applicability in the industrial environments. In addition, it will help in the identification of gaps in the current research and highlighting the opportunities for further research in the area of TSN-5G integration.

Contribution 1 corresponds to Paper A [44] addressing the first subgoal of the thesis $SG_1$: *"To identify challenges and opportunities in the current state-of- the-art of integrated TSN and 5G network"*.

### 3.1.2 Contribution 2: A technique to translate the traffic between TSN and 5G communication technologies

In the second research contribution ($C_2$), we propose a technique to translate the traffic between TSN and 5G communication technologies. This translation acts as a gateway between the two technologies by taking the priority level of TSN frames and mapping them to the 5G Quality of Service (QoS) according to the 3GPP specifications and vice versa. We present a proof-of-concept implementation of the proposed technique in a commonly used TSN network simulator NeSTiNG that is based on OMNeT++. We show that the technique can assist network designers to evaluate various holistic TSN-5G network configurations.

Contribution 2 corresponds to Paper B [45] addressing the second subgoal of the thesis $SG_2$: *"To efficiently translate the traffic and map QoS requirements between TSN and 5G network domains."*.

### 3.1.3 Contribution 3: A novel and efficient mapping algorithm to map different TSN traffic flows to 5G QoS flows

The third research contribution ($C_3$) in this thesis introduces a novel algorithm, called the QoS-MAN, to systematically 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 considered 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 strict QoS. The algorithm uses the application requirements as its input. We define these requirements 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 the packet to a specific 5G QoS flow identifier that fulfill its needs.

Contribution 3 corresponds to Paper C [46] addressing the second subgoal of the thesis $SG_2$: *"To efficiently translate the traffic and map QoS requirements between TSN and 5G network domains."*.

### 3.1.4 Contribution 4: A centralized architectural model to configure the TSN-5G network

The fourth contribution ($C_4$) in this thesis consists of a centralized architectural model to configure the TSN-5G network, and forward traffic from TSN to 5G and vice-versa. The proposed architectural model uses knowledge of the traffic characteristics to carry out a more accurate mapping of quality of service attributes between TSN and 5G. We discussed the main aspects of the architecture, i.e., which devices are involved and how they inter-operate. Furthermore, we proposed a workflow, which defines the different activities required to properly configure a TSN-5G network using the proposed architecture.

Contribution 4 corresponds to Paper D [47] addressing the third subgoal of the thesis $SG_3$: *"To design a centralized architecture to configure the TSN-5G network, and forward traffic from TSN to 5G and vice-versa."*.

## 3.2 Overview of Included Papers

The research contributions are encapsulated in four scientific publications included in the thesis. In this section, we present a summary of the included publications.

### 3.2.1 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), February, 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.

### 3.2.2 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. The plan for the paper was formed in joint discussions with the co-authors. The co-authors have reviewed the paper, after which I have improved it.

### 3.2.3 Paper C

**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.

### 3.2.4 Paper D

**Title:** Work in progress - A centralized configuration model for TSN-5G networks

**Authors:** Zenepe Satka, Inés Álvarez, Mohammad Ashjaei, Saad Mubeen.

**Status:** Published in the 27th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), 2022.

**Abstract:** The integration of Time-Sensitive Networks (TSN) with 5G cellular networks requires a defined architecture for network configuration and management. Although 3GPP specifications provide necessary means for the TSN-5G integration, the operation of such converged TSN-5G network remains an open challenge for the research community. To address this challenge, this paper presents the ongoing work in developing a centralized architectural model to configure the TSN-5G network, and forward traffic from TSN to 5G and vice-versa. Our model uses knowledge of the traffic characteristics to carry out a more accurate mapping of QoS-es between TSN and 5G. To support this mapping technique, we need to define an adequate network architecture.

**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 centralized architectural model to configure the TSN-5G network, and wrote the first draft of the paper. The co-authors have reviewed the paper, after which I have improved it.

### 3.2.5 Mapping of Research Goal to Contributions and Publications

This section provides the mapping of the research contributions and included papers to the defined sub-goals and final goal of this thesis shown in Figure 3.1. There is a one-to-one mapping between the research contributions and publications. The research contributions $C_1$ and $C_4$ address sub-goals $SG_1$ and $SG_3$ respectively. Whereas, both research contributions $C_2$ and $C_3$ address sub-goal $SG_2$.

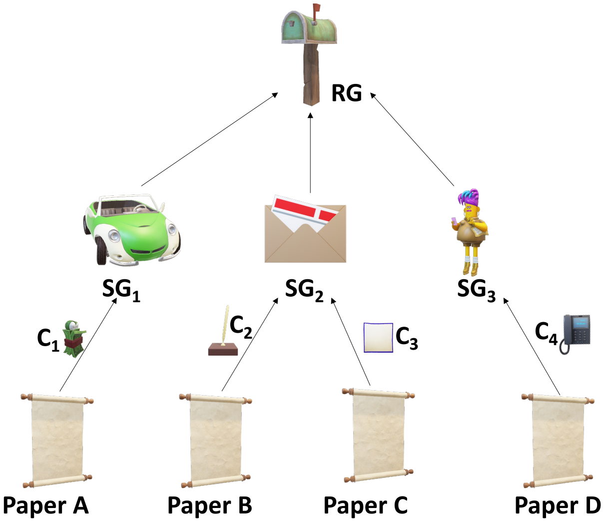


**Figure 3.1:** Mapping among the research sub-goals, research contributions and publications.

# Chapter 4

# Summary and Future Works

With the contributions being discussed, we now turn our attention to conclusions and possible directions for future works.

## 4.1 Summary

In this thesis, we develop new techniques and mechanisms to provide an end-to-end QoSmapping and traffic forwarding of a converged TSN-5G network for real-time applications.

One of the main contributions of this thesis was 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 addresses the first sub-goal of the thesis and it was 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 will help in the identification of gaps in the current research and highlighting the opportunities for further research in the area of TSN-5G integration.

In addition, to address the second sub-goal of this thesis we focus on the traffic forwarding from a TSN to a 5G network providing a translation technique between different communication protocols. 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, to handle the end-to-end QoSrequirements of real-time applications we introduce a novel and efficient mapping algorithm which maps different TSN traffic flows to 5G QoSflows. 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 QoSflow identifier that fulfill the needs.

Furthermore, to address the third sub-goal of the thesis, we introduce a centralized architectural model to configure TSN-5G network using a centralized network configuration entity which appears as a software-defined controller for the whole TSN-5G system.

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. However, it presents significant challenges such as standardization and interoperability between different vendors, time synchronization between both technologies, network security and privacy, as well as technical challenges in understanding of the different architectural trade-offs in a joint TSN-5G architecture.

## 4.2 Future work

Both TSN and 5G are still in the early stages of development and deployment. 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, the need for an integrated TSN-5G network is rapidly growing and a number of companies and organizations are working on its development and implementation.

There exist several core challenges in the state of the art that require the immediate attention of the community to achieve seamless integration of TSN and 5G for industrial applications.

However, our main focus is on handling QoSrequirements and traffic prioritization and forwarding on a TSN-5G network.

As an extension of our previous work on a centralized architectural model for TSN-5G network, we aim at developing a scheduling mechanism to ensure the efficient and predictable delivery of time-sensitive data while allocating efficient amount of radio resources on a 5G network.

In addition, we aim to experimentally analyse the integration of TSN and 5G on a real-world environment implementing different industrial use cases.

# Bibliography

[1] Martin Wollschlaeger, Thilo Sauter, and Juergen Jasperneite. The Future of Industrial Communication: Automation Networks in the Era of the Internet of Things and Industry 4.0. *IEEE Industrial Electronics Magazine*, 11(1):17–27, 2017.

[2] C. S. V. Gutiérrez, L. U. S. Juan, I. Z. Ugarte and V. M. Vilches. Time-sensitive networking for robotics. arXiv preprintarXiv:1804.07643, 2018.

[3] Frederick Prinz, Michael Schoeffler, Armin Lechler, and Alexander Verl. Dynamic real-time orchestration of I4.0 components based on time-sensitive networking, 06 2018. Procedia CIRP, vol. 72, pp. 910–915.

[4] Avnu Alliance. Networking for industrial machine building, V. 1.0, 2014. White Paper.

[5] Libing Deng, Guoqi Xie, Hong Liu, Yunbo Han, Renfa Li, and Keqin Li. A survey of real-time ethernet modeling and design methodologies: From avb to tsn. *ACM Comput. Surv.*, 55(2), 01 2022.

[6] Lucia Lo Bello and Wilfried Steiner. A perspective on IEEE Time-sensitive Networking for Industrial Communication and Automation Systems. *Proceedings of the IEEE*, 107(6):1094–1120, 2019.

[7] Jeffrey G. Andrews, Stefano Buzzi, Wan Choi, Stephen V. Hanly, Angel Lozano, Anthony C. K. Soong, and Jianzhong Charlie Zhang. What will 5G be? *IEEE Journal on Selected Areas in Communications*, 32(6):1065–1082, 2014.

[8] Noura Aljeri and Azzedine Boukerche. Mobility Management in 5G-Enabled Vehicular Networks: Models, Protocols, and Classification. *ACM Comput. Surv.*, 53(5), 09 2020.

[9] Technical Specification Group Services and System Aspects; System architecture for the 5G system (5GS)(Release 16). Technical report, 3GPP TS 23.501, 10 2020.

[10] Radio Resource Control (RRC) Protocol Specification. Technical report, 3GPP TS 38.331, 2020.

[11] 5G ACIA. 5G for Connected Industries and Automation, 2019. white paper.

[12] Amitabha Ghosh, Andreas Maeder, Matthew Baker, and Devaki Chandramouli. 5G Evolution: A View on 5G Cellular Technology Beyond 3GPP Release 15. *IEEE Access*, 7:127639–127651, 2019.

[13] Jorge Navarro-Ortiz, Pablo Romero-Diaz, Sandra Sendra, Pablo Ameigeiras, Juan J. Ramos-Munoz, and Juan M. Lopez-Soler. A Survey on 5G Usage Scenarios and Traffic Models. *IEEE Communications Surveys Tutorials*, 22(2):905–929, 2020.

[14] Gordana Dodig-Crnkovic. Scientific Methods in Computer Science. *Proceedings of the Conference for the Promotion of Research in IT at New Universities and at University Colleges*, 12 2002.

[15] Barbara Kitchenham and Pearl Brereton. A systematic review of systematic review process research in software engineering. *Information and Software Technology*, 55(12):2049–2075, Dec. 2013.

[16] Arne Neumann, Lukasz Wisniewski, Rakash SivaSiva Ganesan, Peter Rost, and Jürgen Jasperneite. Towards integration of Industrial Ethernet with 5G mobile networks. In *2018 14th IEEE International Workshop on Factory Communication Systems (WFCS)*, pages 1–4, Imperia, Italy, 2018. IEEE.

[17] Lukasz Wisniewski, Markus Schumacher, Juergen Jasperneite, and Sebastian Schriegel. Fast and simple scheduling algorithm for PROFINET IRT networks. In *2012 9th IEEE International Workshop on Factory Communication Systems*, pages 141–144, 2012.

[18] Norman Finn. Introduction to Time-Sensitive Networking. *IEEE Communications Standards Magazine*, 2(2):22–28, 2018.

[19] Mohammad Ashjaei, Lucia Lo Bello, Masoud Daneshtalab, Gaetano Patti, Sergio Saponara, and Saad Mubeen. Time-Sensitive Networking in automotive embedded systems: State of the art and research opportunities. *Journal of Systems Architecture*, 117:102137, 2021.

[20] Lucia Lo Bello, Riccardo Mariani, Saad Mubeen, and Sergio Saponara. Recent Advances and Trends in On-Board Embedded and Networked Automotive Systems. *IEEE Transactions on Industrial Informatics*, 15(2):1038–1051, 2019.

[21] IEEE Standard for Local and metropolitan area networks – Bridges and Bridged Networks - Amendment 25: Enhancements for Scheduled Traffic. Technical report, IEEE Std 802.1Qbv-2015, 2016.

[22] Luxi Zhao, Paul Pop, Zhong Zheng, and Qiao Li. Timing Analysis of AVB Traffic in TSN Networks Using Network Calculus. In *2018 IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS)*, pages 25–36, 2018.

[23] IEEE Standard 802.1Qcc. IEEE Standard for Local and Metropolitan Area Networks–Bridges and Bridged Networks–Amendment 31: Stream Reservation Protocol (SRP) Enhancements and Performance Improvements, 10 2018.

[24] Qazi Kamal Ud Din Arshad, Ahsan Ullah Kashif, and Ijaz Mansoor Quershi. A review on the evolution of cellular technologies. In *2019 16th International Bhurban Conference on Applied Sciences and Technology (IBCAST)*, pages 989–993, 2019.

[25] Rony Kumer Saha, Shinobu Nanba, Kosuke Nishimura, Young-bin Kim, and Kosuke Yamazaki. RAN Architectural Evolution Framework toward 5G and Beyond Cellular-An Overview. In *2018 IEEE 29th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, pages 592–593, 2018.

[26] Technical Specification Group Services and System Aspects; (Release 15). Technical report, 3GPP TS 21.915, 12 2018.

[27] Alexandros Kaloxylos. Network Slicing for 5G Networks: A Survey and an Analysis of Future Trends. In *Proceedings of the 21st Pan-Hellenic Conference on Informatics*, PCI 2017, New York, NY, USA, 2017. Association for Computing Machinery.

[28] Imtiaz Parvez, Ali Rahmati, Ismail Guvenc, Arif I. Sarwat, and Huaiyu Dai. A Survey on Low Latency Towards 5G: RAN, Core Network and Caching Solutions. *IEEE Communications Surveys Tutorials*, 20(4):3098–3130, 2018.

[29] Jeffrey G. Andrews, Stefano Buzzi, Wan Choi, Stephen V. Hanly, Angel Lozano, Anthony C. K. Soong, and Jianzhong Charlie Zhang. What will 5G be? *IEEE Journal on Selected Areas in Communications*, 32(6):1065–1082, 2014.

[30] Shanshan Zhao Shancang Li, Li Da Xu. 5G internet of things: A survey. *Journal of Industrial Information Integration*, 10:1–9, 2018.

[31] Godfrey Anuga Akpakwu, Bruno J. Silva, Gerhard P. Hancke, and Adnan M. Abu-Mahfouz. A Survey on 5G Networks for the Internet of

Things: Communication Technologies and Challenges. *IEEE Access*, 6, 2018.

[32] M. A. Siddiqi, H. Yu, J. Joung. 5G ultra-reliable low-latency communication implementation challenges and operational issues with IoT devices, September 2019.

[33] Mikko Säily, Carlos Barjau Estevan, Jordi Joan Gimenez, Fasil Tesema, Wei Guo, David Gomez-Barquero, and De Mi. 5G Radio Access Network Architecture for Terrestrial Broadcast Services. *IEEE Transactions on Broadcasting*, 66(2):404–415, 2020.

[34] A. Zaidi, A. Bränneby, A. Nazari, M. Hogan, and C. Kuhlins. Cellular IoT in the 5G era: Realizing cellular IoT for industrial transformation, June 2019. [Online]. Available: https://www.ericsson.com/en/reports-and-papers/white-papers/cellular- iot-in-the-5g-era.

[35] Bernd Holfeld, Dennis Wieruch, Thomas Wirth, Lars Thiele, Shehzad Ali Ashraf, Jorg Huschke, Ismet Aktas, and Junaid Ansari. Wireless Communication for Factory Automation: an opportunity for LTE and 5G systems. *IEEE Communications Magazine*, 54(6):36–43, 2016.

[36] Mykola Beshley, Natalia Kryvinska, Marian Seliuchenko, Halyna Beshley, Elhadi M. Shakshuki, and Ansar-Ul-Haque Yasar. End-to-End QoS "Smart Queue" Management Algorithms and Traffic Prioritization Mechanisms for Narrow-Band Internet of Things Services in 4G/5G Networks. *Sensors*, 20(8), 2020.

[37] TS 123 501: 5G; System architecture for the 5G System (5GS). Technical report, ETSI TS 123 501, 10 2020.

[38] Fernando Rodini. QoS/QoE developments in 4G-IoT & 5G technologies. *ITU Workshop on Telecommunications Service Quality*, pages 27–29, 2017.

[39] Technical Specification Group Services and System Aspects; Study on enhancement of 5G System (5GS) for vertical and Local Area Network (LAN) services (Release 16). Technical report, 3GPP TR 23.734, 06 2019.

[40] Istvan Godor, Michele Luvisotto, Stefano Ruffini, Kun Wang, Dhruvin Patel, Joachim Sachs, Ognjen Dobrijevic, Daniel P. Venmani, Olivier Le Moult, Jose Costa-Requena, Aapo Poutanen, Chris Marshall, and Janos

Farkas. A Look Inside 5G Standards to Support Time Synchronization for Smart Manufacturing. *IEEE Communications Standards Magazine*, 4(3):14–21, 2020.

[41] Maximilian Schüngel, Steven Dietrich, David Ginthör, Shun-Ping Chen, and Michael Kuhn. Analysis of time synchronization for converged wired and wireless networks. In *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, volume 1, pages 198–205, Vienna, Austria, 2020. IEEE.

[42] Ericsson, Network architecture domains, [Online]. Available: https://www.ericsson.com/en/future-technologies/architecture/network-architecture-domains.

[43] Ana Larrañaga, M. Carmen Lucas-Estañ, Imanol Martinez, Iñaki Val, and Javier Gozalvez. Analysis of 5G-TSN Integration to Support Industry 4.0. In *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, volume 1, pages 1111–1114, Vienna, Austria, 2020. IEEE.

[44] Zenepe Satka, Mohammad Ashjaei, Hossein Fotouhi, Masoud Daneshtalab, Mikael Sjödin, and Saad Mubeen. A comprehensive systematic review of integration of time sensitive networking and 5g communication. *Journal of Systems Architecture*, 138:102852, 2023.

[45] Zenepe Satka, David Pantzar, Alexander Magnusson, Mohammad Ashjaei, Hossein Fotouhi, Mikael Sjödin, Masoud Daneshtalab, and Saad Mubeen. Developing a translation technique for converged tsn-5g communication. In *2022 IEEE 18th International Conference on Factory Communication Systems (WFCS)*, pages 1–8, 2022.

[46] Zenepe Satka, Mohammad Ashjaei, Hossein Fotouhi, Masoud Daneshtalab, Mikael Sjödin, and Saad Mubeen. Qos-man: A novel qos mapping algorithm for tsn-5g flows. In *2022 IEEE 28th International Conference on Embedded and Real-Time Computing Systems and Applications (RTCSA)*, pages 220–227, 2022.

[47] Zenepe Satka, Inés Álvarez, Mohammad Ashjaei, and Saad Mubeen. Work in progress: A centralized configuration model for tsn-5g networks. In *2022 IEEE 27th International Conference on Emerging Technologies and Factory Automation (ETFA)*, pages 1–4, 2022.

[48] Security Architecture and Procedures for 5G System. Technical report, 3GPP TS 33.501, August 2020.

[49] Study on Enhancements for Cyber-Physical Control Applications in Vertical Domains. Technical report, 3GPP TR 22.832, 2019.

[50] IEEE Std 802.1QTM. IEEE Standard for Local and Metropolitan Area Networks - Virtual Bridged Local Area Networks - Amendment 07: Multiple Registration Protocol. *Std 802.1ak-2007 (Amendment to IEEE Std 802.1QTM-2005)*, pages 1–115, 2007.

[51] 5G ACIA. Integration of 5G with Time-Sensitive Networking for Industrial Communications, 2021. white paper.

[52] Maximilian Schüngel, Steven Dietrich, Ludwig Leurs, David Ginthör, Shun-Ping Chen, and Michael Kuhn. Advanced Grandmaster Selection Method for Converged Wired and Wireless Networks. In *2021 22nd IEEE International Conference on Industrial Technology (ICIT)*, volume 1, pages 1007–1014, Valencia, Spain, 2021. IEEE.

[53] Technical Specification Group Services and System Aspects; Study on Scenarios and Requirements for Next Generation Access Technologies (Release 14). Technical report, 3GPP Rep. 38.913, 2017.

[54] Dongmyoung Kim Junseok Kim and Sunghyun Choi. 3GPP SA2 architecture and functions for 5G mobile communication system. In *ICT Express*, volume 3, pages 1–8. Elsevier, 2017.

# Part II

# Included Papers

# Chapter 5

# Paper A:
# A Comprehensive Systematic Review of Integration of Time Sensitive Networking and 5G Communication

Zenepe Satka, Mohammad Ashjaei, Hossein Fotouhi, Masoud Daneshtalab,
Mikael Sjödin, Saad Mubeen.
Journal of Systems Architecture (JSA), 2022.

## 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.

## 5.1 Introduction

There is an urgent need to support ultra-reliable, high-bandwidth, low-latency and predictable communication in many contemporary and future industrial applications [1, 2]. Examples of these applications include autonomous driving, autonomous construction sites and mines, collaborating robots, augmented and virtual reality, to mention a few [3–5]. The end-to-end communication in these applications is achieved by combining wired networks (for onboard communication) and wireless networks (for remote communication). The end-to-end (E2E) latency in these applications often ranges from milliseconds for wired onboard communication to microseconds for wireless communication [6, 7].

Time-sensitive networking (TSN) is a set of standards for Ethernet-based communication, where the main focus is on providing low-latency and low-jitter for time-sensitive traffic, and even to provide deterministic message transmission over switched Ethernet [6, 8–11]. Since it is a wired network, it limits the connection only to the areas where a wired connection is feasible while missing the flexibility of a mobile connection.

The fifth generation of wireless telecommunications (5G) [12, 13] can provide the flexibility and scalability required of the mentioned applications. 5G supports real-time applications by using a service called Ultra-Reliable Low Latency Communication (URLLC) which is part of the 3rd Generation Partnership Project (3GPP) Releases [14–17]. URLLC is a promising candidate for real-time wireless communication that can support latency down to 1ms and reliability up to 99.999% [18–20].

A converged wired and wireless network integrating TSN and 5G is needed to achieve real-time requirements, determinism as well as mobility and scalability of communication in contemporary and future industrial applications. Moreover, the integration of TSN with 5G offers improved Quality of Service (QoS) for time-sensitive applications, such as autonomous driving, industrial automation, and virtual reality. By integrating TSN with 5G, industries will take advantage of the benefits of both technologies to enable new use cases and applications. To achieve the E2E QoS requirements of a TSN-5G network a significant effort is required due to the large dissimilarity of the considered systems.

Several core challenges are encountered when integrating the TSN and 5G technologies. Some notable challenges include understanding of the different architectural trade-offs in a joint TSN-5G architecture, time synchronization between the two technologies, simulation, and implementation of a TSN-5G network in a real-world environment, among others. Various initiatives aimed at addressing these challenges. For example, the overview of relevant architecture aspects and the relevant features and processes are described in 3GPP TS 23.501, TS 23.502, TS 23.503, and 5G-ACIA [18]. The interaction between the two technologies is part of 3GPP specifications and there are many research works in this regard. In this paper, we construct a structured map of the existing literature on the integration of TSN and 5G communication technologies. We show that there exist several gaps in the state of the art that require the immediate attention of the community to achieve a seamless integration of TSN and 5G for industrial applications.

### 5.1.1 Paper Contributions

This Systematic Literature Review (SLR) identifies the research studies conducted in the area of TSN and 5G integration. The main goal of this SLR is to provide a detailed investigation of state of the art on TSN-5G integration and provide a fully-concentrated and well-organized classification scheme introduced in Section III. This will help the researchers and practitioners in identifying and understanding the existing solutions and their applicability in industrial environments. Another contribution of this SLR is the identification of gaps in the current research and highlighting the opportunities for further research in the area of TSN-5G integration.

In this article, from an initial set of 189 studies, we identified 82 primary studies[1]. We analyzed these studies in detail, following a structured data extraction, analysis, and synthesis process. A summary of the resulting highlights of our study is as follows:

- The efforts in this research area started in 2018, after the initial delivery of 3GPP Release 15 in late 2017.

- 73% of the primary studies address time synchronization between the two technologies, which still represents a significant challenge in the integration of these two technologies.

- In the context of time synchronization between the two technologies, the transparent clock approach is mostly preferred over the boundary clock approach.

- 74% of the primary studies follow an integration architecture, which conforms to the 3GPP releases.

---

[1] Primary studies refer to the state of the art publications that are relevant to the goal of this SLR study.

- 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.

- Most of the primary studies remain generic without focusing on a specific domain.

- The technical contributions provided by the majority of the existing studies are focused on the integration architecture of TSN and 5G. In this regard, the majority of these studies provide solution proposals or validation research, while missing other types of research such as evaluation research, or experience papers. None of the primary studies have provided a tool as a contribution. This indicates that there is an urgent need for provisioning of tools that incorporate the existing techniques or new techniques for TSN-5G integration.

### 5.1.2 Paper Outline

The rest of the paper is organized as follows. Section 5.2 describes the research method in detail. Section 5.3 provides a detailed overview of our data extraction form. Section 5.4 shows the vertical results of our study, while Section 5.5 illustrates the horizontal results. Section 5.6 presents Fleiss Kappa statistical analysis that we used to mitigate threats to validity. In Section 5.7, we discuss the potential threats to the validity of our study and how we mitigate them. Section 5.8 presents similar works to our study. Section 5.9 concludes the paper and presents the future work.

## 5.2 Study Selection Process

This study is conducted and fulfilled based on the well-known guidelines presented in [21] and [22]. The process is divided into 3 main phases: (i) planning, (ii) conducting, and (iii) documenting as shown in Figure 5.1.

**Planning**. The main objective in the planning phase is to identify the research questions (RQs) and the need for a review of related works and approaches that are performed within the scope of TSN-5G integration. From this phase, a detailed protocol was defined following the specified steps to conduct the study systematically.

**Conducting**. This phase starts with the search and selection step, where the automatic string search is performed in the four largest databases hosting the research in the domains of computer science, computer engineering, software

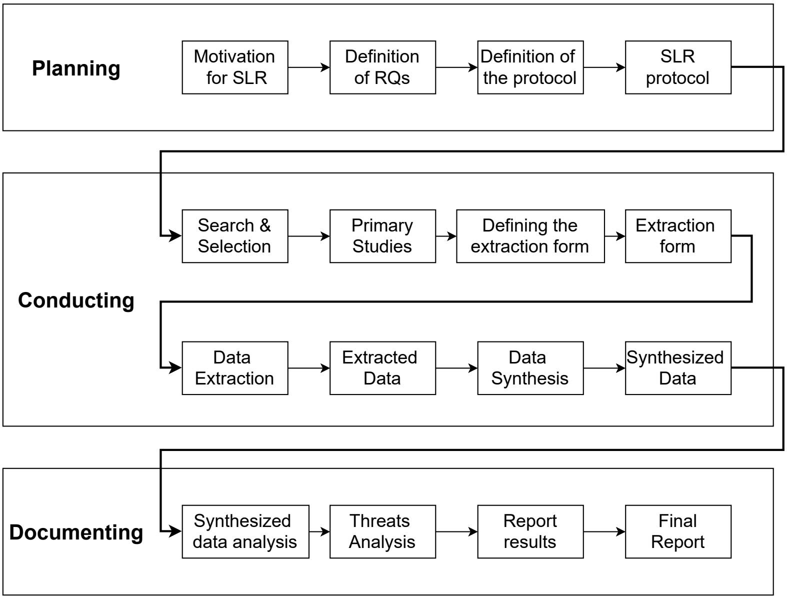


**Figure 5.1:** An overview of the SLR process.

engineering, and systems engineering, among others. Based on the authors' knowledge of the targeted research domain, three primary studies [23–25] were chosen from the search pool to be considered in the extraction form of the review process. A set of parameters were identified for the classification scheme that was used for the data extraction form of our study. We specified those parameters by systematically applying the standard keywording process [26]. After fulfilling the data extraction form for each of the research studies, we analyzed and synthesized the extracted data to address the research questions (see Section 5.2.1) posed in this SLR.

**Documenting**. In this phase, we carried out a detailed analysis of the extracted data. Furthermore, we identified possible threats to the validity of our study. A comprehensive analysis was performed for threat validation and verification. This article was written to document and illustrate the performed study in detail.

### 5.2.1 Research goal and questions

The goal of this SLR is:

> "*to classify the technical characteristics as well as to investigate research trends, identify gaps in the state of the art, and highlight*

*open challenges and future directions in the research on integration of TSN and 5G technologies for end-to-end communication in the industrial applications.*"

To achieve this goal, the following research questions are identified based on the authors' knowledge of the research area:

**RQ1:** *What are the technical characteristics of TSN and 5G integration?*
**Objective:** to identify and classify existing approaches and techniques for TSN and 5G integration in terms of their technical characteristics.

- **RQ1.1:** *How is resource management conducted in TSN-5G integrated architectures?*
  **Objective:** to classify studies in terms of resource management aspects like configuration model and scheduling.
- **RQ1.2:** *How is the traffic flow managed between TSN and 5G networks?*
  **Objective:** to classify studies related to the different protocols and models they use to manage the traffic flow.
- **RQ1.3:** *Which time synchronization technique is used to achieve a deterministic network environment?*
  **Objective:** to classify the studies in terms of their time synchronization approaches.
- **RQ1.4:** *Which integration architectures are proposed by the research community and what kind of properties do they present?*
  **Objective:** to identify different integration approaches and classify the studies regarding the properties they address.

**RQ2:** *What are the publication trends of research on TSN and 5G integration?*
**Objective:** to classify a set of relevant studies in order to assess trends and venues over time.

**RQ3:** *What are the limitations of TSN-5G integration?*
**Objective:** to identify current research gaps and limitations with respect to the state of the art research on TSN-5G integration.

The answer to RQ1 will require a detailed investigation of the technical part of this integration, specifically in answering the following questions: (i) what are the different aspects of this integration? (ii) how two different networks can communicate with each other to have a fully converged network?

And (iii) what are the core challenges identified in the existing literature. The answer to RQ2 is expected to provide a detailed overview of the current publication trends, research types, and venues. Finally, the answer to RQ3 will assist the research community in understanding whether there is room for improvement in the existing approaches and further research opportunities in this research area.

### 5.2.2 Search and selection strategy

After defining the research goal and research questions of our study, we gather the relevant studies available in the research area as presented in Figure 5.2.

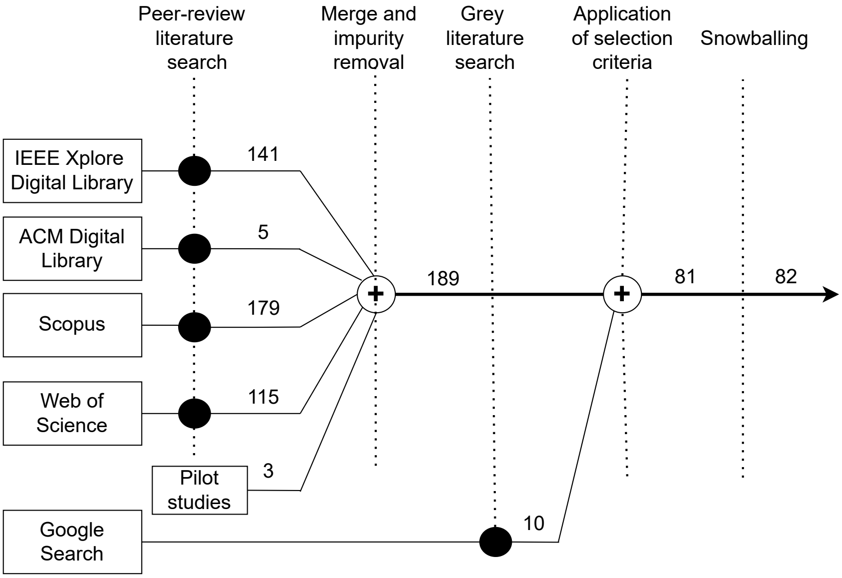


**Figure 5.2:** Search and selection process.

Before proceeding with the search pool, we first manually select a set of pilot studies based on the authors' knowledge of the targeted area. To select the pilot studies, the authors informally screened the available literature on TSN-5G integration, and selected the followed pilot studies that have a considerable impact on the research area.

1. "5G Industrial Networks With CoMP for URLLC and Time Sensitive Network Architecture" (2019) [23].
2. "Extending Accurate Time Distribution and Timeliness Capabilities Over the Air to Enable Future Wireless Industrial Automation Systems"

(2019) [24].

3. “A Look Inside 5G Standards to Support Time Synchronization for Smart Manufacturing” (2020) [25].

We use these works to formulate the search string and to identify some of the parameters of our data extraction form. Moreover, we perform a manual search in the so-called grey literature (e.g., web pages, forums, etc) on the Google search engine, to identify any white paper that provides relevant information for our study. Two parallel activities were carried out: the *review of the peer-reviewed literature*, and the *review of the grey literature*.

### Automatic search

To identify the relevant studies, we conduct an automatic search on four of the largest and most complete databases in computer science, computer engineering, software engineering, and systems engineering: IEEE Xplore Digital Library, ACM Digital Library, Scopus, and Web of Science as shown in Table 5.1. The selection of these electronic databases and indexing systems was motivated by their high accessibility and the fact that they export search results to well-defined and computation-amenable formats. Furthermore, one of the strongest points is the fact that these databases are recognized as being effective means to conduct systematic literature reviews [27].

**Table 5.1:** Electronic databases and indexing systems considered in this search.

| **Name** | **Type** | **URL** |
|---|---|---|
| IEEE Xplore Digital Library | Electronic database | `www.ieeexplore.ieee.org` |
| ACM Digital Library | Electronic database | `www.dl.acm.org` |
| SCOPUS | Indexing system | `www.scopus.com` |
| Web of Science | Indexing system | `www.webofknowledge.com` |

We define the search string based on the keywords extracted from the research questions and the pilot studies. We use the same search string in all databases and the process we adapted is based on the search fields required by the digital libraries: title, abstract, and keywords. Our search string is as follows:

```
  (("Time Sensitive Network*" OR "Time-Sensitive Network*" OR
"Time Sensitive Communication" OR "TSN") AND (("5G″ OR "URLLC")
```

```
OR (("5G”) AND ("Virtual bridge” OR "Transparent Bridge” OR
"ULL" ))))
```

The search results include 141 publications in IEEE Xplore Digital Library, 5 in ACM Digital Library, 179 in Scopus, and 115 in Web of Science.

### Impurity and duplicates removal

Since some of the research studies can be indexed in more than one database, we first removed the duplicates. Then we addressed impurities in our searches such as abstracts and tutorials. We performed this process by using a tool called StArt [28] that supports the SLR process. After removing the duplicates, we achieved 189 publications – see Figure 5.2.

### Grey literature search

To collect the grey literature, we follow the guidelines for including grey literature and conducting multivocal literature reviews in software engineering [29]. According to these guidelines we target Google Search Engine, performing the automatic search with the same string search as before, and a manual search based on our knowledge of the targeted research area. The grey literature gave us 10 more primary studies as in Figure 5.2.

### Application of selection criteria

In the next step, we apply our inclusion and exclusion criteria to all the publications to identify the primary studies that correspond to the relevant publications for this study. In this step, we classify each publication as "Relevant", "Non-Relevant" and "Not Clear". We perform this classification by reviewing the title, abstract, and keywords of each publication. The publication is considered relevant if it addresses the goal and purpose of this study. If the publication is out of the scope of this study, then it is considered non-relevant. Otherwise, if we cannot classify the publication as relevant or non-relevant based on the abstract, title, and keywords, it is set as not clear. In this case, we perform full-text skimming of the publication with the aim of classifying it as relevant or non-relevant. The selection criteria are as follows.

### Inclusion criteria for Peer-reviewed literature

**ICP1)** The research study addresses the integration of TSN and 5G.

**ICP2)** The research study is written in English.

**ICP3)** The research study is a peer-reviewed publication, i.e., published in a peer-reviewed journal, workshop, conference, or book.

**ICP4)** The research study is available as full-text.

**Inclusion criteria for Grey literature**

**ICG1)** Web page or white paper reporting on an integration technique/framework/architecture for TSN and 5G.

**ICG2)** Web page or white paper reporting on a formalization and/or implementation of the proposed TSN and 5G integration approach.

**ICG3)** Web page or white paper is in English.

**ICG4)** Web page or white paper is freely accessible.

**Exclusion criteria for Peer-reviewed literature**

**ECP1)** Secondary and tertiary studies such as systematic literature reviews, surveys, etc.

**ECP2)** Studies in the form of tutorial papers, short papers, editorials, manual, or poster papers because these types of publications do not provide enough information to answer the posed questions.

**Exclusion criteria for Grey literature**

**ECG1)** Web page or white paper that does not clearly discuss integration of TSN and 5G.

**ECG2)** Videos, webinars, books, etc. since they are too time-consuming to be considered for this study.

Even though the secondary/tertiary and other studies are excluded from the search pool, we consider them in identifying any important issues to be considered in our study and for providing a summary of what is already known on TSN-5G integration.

After removing the duplicates and applying the inclusion/exclusion criteria to both the peer-reviewed literature and the grey literature, we managed to get a set of 81 primary studies. The majority of primary studies were excluded due to the removal of impurities and duplicates (251 studies). 91 primary studies were excluded due to not addressing the goal and purpose of this study (not fulfilling ICP1). Moreover, 1 primary study was excluded as it wasn't written in English (not fulfilling ICP2), and 8 primary studies were excluded as they weren't available as full text (not fulfilling ICP4). In addition, 33 primary studies were excluded due to being secondary and tertiary studies (ECP1), and 6 primary studies were excluded due to being editorial papers, or posters (ECP2). Note that some of the studies were excluded as they did not fulfill (or fulfilled) more then 1 inclusion (exclusion) criteria.

### Snowballing

To mitigate any potential bias regarding the construct validity of our study, we perform a closed recursive backward and forward snowballing activity[2] [30]. The starting set of our search is the set of primary studies presented earlier and the pool of selected studies after the second string search as shown in Figure 5.2. From the recursive backward and forward snowballing, we found two more relevant studies. The full text of one of these studies is not available which violates the inclusion criteria ICG4. Therefore, we remove this study and add the remaining study to the pool of primary studies, which makes the total number of primary studies equal to 82.

The number of relevant studies is low as we expected because the targeted research area is still in its infancy. Note that the integration of TSN and 5G technologies is discussed for the first time in the specification of 5G in 2018. Thus, the research on the integration of TSN and 5G technologies has not gained maturity.

## 5.3 Data Extraction

In this phase, we create a data extraction form (classification form) that is used to extract the required data from the primary studies. We follow a systematic process based on keywording for defining the parameters in the top levels of the data extraction form in Figure 5.3. Furthermore, we use keywording to extract data from the primary studies accordingly.

The goal of the keywording is to effectively develop an extraction form that can fit existing studies while taking their characteristics into account [26]. We collect the keywords and concepts by studying the full text in the primary studies. After collecting the keywords and concepts, we perform a clustering operation to organize them according to the identified categories. The clustering operation is similar to the sorting phase of the grounded theory method-

---

[2] Backward snowballing refers to scouring the references sections of papers that are already included in the review, while forward snowballing refers to tracking articles that had subsequently cited any of the papers included in the review.

ology [31]. During this phase, we collect any additional information that was marked relevant but did not fit within the data extraction form. We refine the data extraction form after the revision of the collected additional information if needed. The previously analyzed primary studies are re-analyzed according to the refined data extraction form. The process is completed only when all the primary studies are analyzed. The final set of analyzed primary studies includes 82 publications[3]. We provide a detailed overview of the data extraction form in the following subsections.

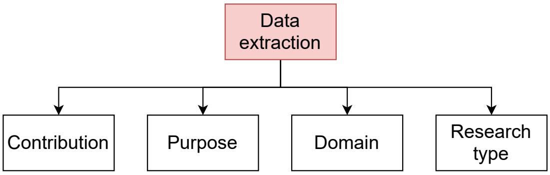


**Figure 5.3:** The top-level categories in the data extraction form.

## 5.3.1 Contribution

This top-level category captures the research contributions concerning TSN-5G integration in the primary studies. Figure 5.4 depicts the internal hierarchy of the research contribution category. It consists of three sub-categories: (i) technical contribution, (ii) contribution type, and (iii) maturity level of the contribution. These categories are described as follows.

### Technical contribution

This category describes what technical contribution is provided by a primary study. It can be further classified into resource management, flow management, time synchronization, and integration architecture.

**The resource management** category refers to how the TSN-5G integrated system's resources, including configuration models and scheduling are managed in a primary study [32]. Note that we focus on the data extraction corresponding to the resource management in integrated TSN and 5G networks. We categorize the configuration models according to the IEEE 802.1QCC (2018) [33] as follows:

- *Fully Distributed model:* All the end stations communicate their requirements directly using the Stream Reservation Protocol (SRP) [33]. SRP is

---

[3] The final set of primary studies corresponds to studies published until **January 21, 2023**, which corresponds to the last day of our search.

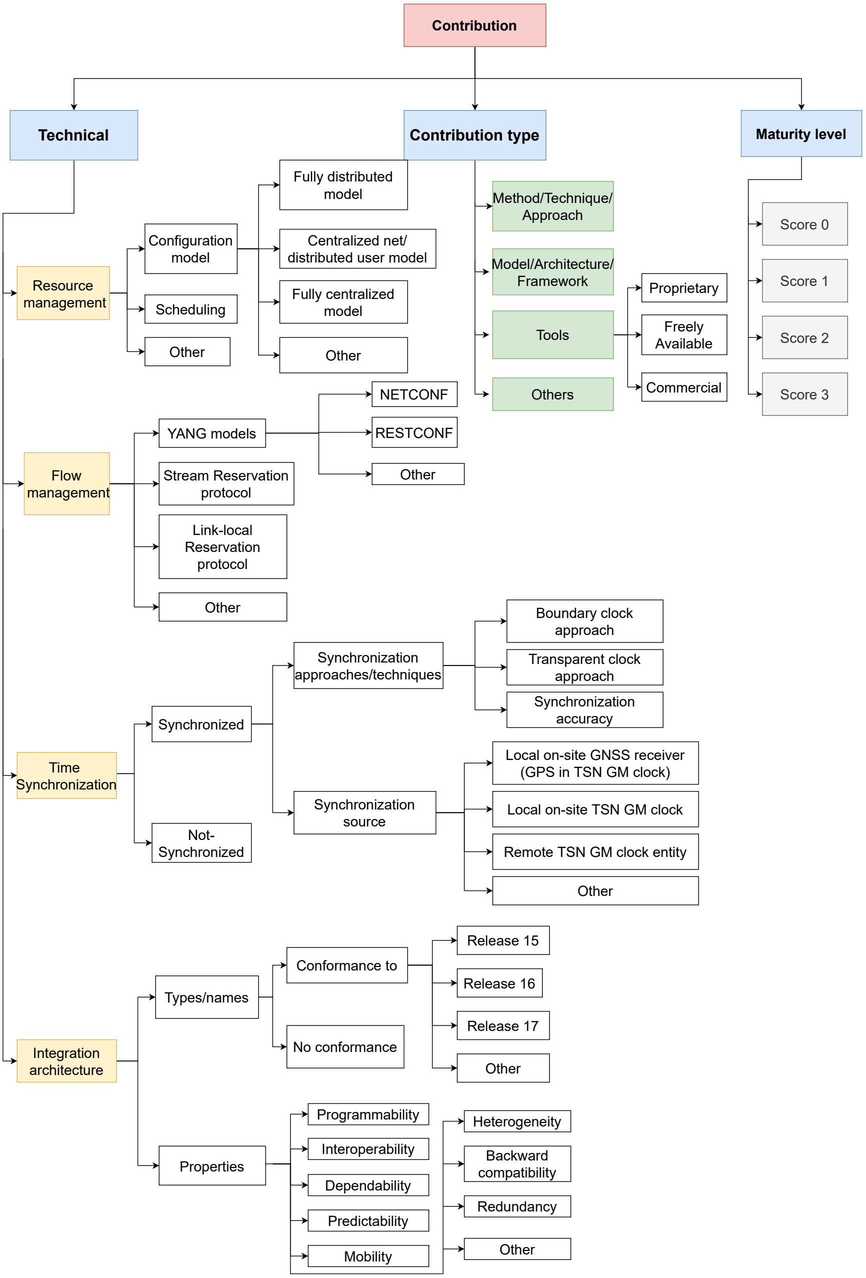


**Figure 5.4:** Data extraction, considering all the main topics in terms of technical issues, types of contributions, and maturity level.

a standard that provides mechanisms to reserve bandwidth per queue on the path of a frame. In SRP, a sender can request a reservation for a certain amount of bandwidth in order to transmit a data stream. The reservation request is sent to a reservation server, which determines whether the requested amount of bandwidth is available and, if yes, it allocates it to the sender. The sender can then transmit the data stream using the reserved bandwidth part. Some potential research directions on SRP may be security enhancement, scalability, integration with other protocols, etc.

- *Centralized network/distributed user model:* There exists a centralized entity called Centralized Network Configuration (CNC) that gathers the information about bridge (TSN switch) capabilities and uses a remote management protocol to perform functions like scheduling, resource reservation and other types of configuration.

- *Fully Centralized model:* This model contains, in addition to the CNC, an entity called the Centralized User Configuration (CUC) that collects all user requirements and interacts with the CNC to decide the topology and scheduling of the network.

**The flow management** category refers to data models or protocols that enables users or operators to dynamically discover, configure, monitor, and report the bridge and end station capabilities [7]. Among several models and languages, the prominent one in the context of TSN and 5G is the YANG model that is used to model configuration data, state data, Remote Procedure Calls (RPCs), and notifications for network management protocols [34]. The YANG model is a formal contract language used for networking, and widely adopted in industries. This is the main motivation why the TSN Task Group decided to establish IEEE 802.1QCP standard to support YANG data modeling. The YANG model is used by the widely accepted protocols, such as NETCONF and RESTCONF, to simplify network configuration, as described below.

- NETCONF is a network management protocol which provides mechanisms to install, manipulate, and delete the configuration of network devices [35]. It is used by the centralized entity of a TSN configuration model (CNC) to configure the switches following a client-server model [36].

- RESTCONF is a network management protocol used to provide the Create, Read, Update, Delete (CRUD) operations on a conceptual data store containing YANG-defined data [37]. It provides an interface to NETCONF data stores leveraging the HTTP methods. In the fully centralized TSN configuration model, it appears as an interface between the CNC and CUC entities.

In addition to the above well-known models, Stream Reservation Protocol (SRP) [33] and Link-Local Reservation Protocol (LLRP) [38] are the flow management protocols used solely in TSN and wireless networks, respectively. They help in improving the performance and reliability of the network by ensuring necessary resources to critical devices and traffic.

**Time synchronization** category refers to the synchronization of TSN and 5G to achieve a whole unified and converged network. Synchronization may vary depending on the time synchronization approach and/or the source of synchronization. We also consider the studies that do not address the time synchronization approach. We categorize time synchronization approaches according to TR 23.734 [39] as follows:

- *Boundary clock approach:* The 5G Radio Access Network (RAN) has a direct connection to the TSN master clock and the timing information is provided to User Equipment (UE) via the 5G broadcast channels.

- *Transparent clock approach:* This approach uses the generalized Precision Time Protocol (PTP) [40] messages to achieve synchronization. The gPTP is a network protocol used to synchronize the distributed clocks within a communication network. The synchronization of clocks between network devices is achieved by passing relevant time event messages [41].

Even though the 3GPP working group addresses synchronization accuracy in the range of hundreds of nanoseconds, this accuracy still depends on the suggested approach.

**The integration architecture** category refers to the proposed TSN-5G architecture. This architecture can either conform or not conform to the 3GPP Releases. In the latter case, the architecture is often designed according to the authors' knowledge of the targeted area. Most of the works follow the 3GPP Releases, which are developed in a backward compatible manner by the 3GPP working group. Release 17 is still under development but there are several researchers that already refer to this release in their works.

In addition, there are different properties of the architectures that can be addressed. We identify the following core properties:

- *Programmability:* using different algorithms to dynamically reprogram the nodes. The current effort on network programmability is mostly centered around the separation of the data and control planes [42,43].
- *Interoperability:* different networks can communicate easily without the need for additional tools or interfaces. This concept is not only related to communication but also to the specification and implementation of an application [44]. Interoperability can be categorized with respect to the resources, protocols, services, and timeliness of the communication. Further definitions of interoperability are presented in [45,46].
- *Dependability:* the ability of a system to provide services that can be trusted within a time period. It includes the system's availability, reliability, maintainability, maintenance support, and performance and in some cases, it may include durability, safety and security [47,48].
- *Predictability:* is related to proving, demonstrating, or verifying the fulfillment of the system's timing requirements. In the artificial intelligence community, predictability is also related to the support for mechanisms that predict beforehand the future state of the system [49,50].
- *Mobility:* refers to network mobility. Based on some measurement reports, the network may possibly move (i.e., handover [51]) the mobile terminal connection from the serving cell to that neighbor cell, so the mobile terminal will get better radio conditions [52].
- *Heterogeneity:* in the sense of a network containing different types of nodes as in [53]. Software, hardware, and technology variation between mobile devices cause heterogeneity [54].
- *Backward compatibility:* is the ability of a network to be compatible with earlier versions, meaning that all the previous features will be valid in the new version [55]. For example, 5G devices are able to operate on earlier-generation networks (4G, 3G, etc).
- *Redundancy:* is the duplication of network instances such as devices or lines of communication to increase the system's reliability and to reduce the risk of failures. It is one of the mechanisms to provide reliable data transfers [56,57].

### Contribution type

Another sub-category of the contribution is the contribution type. It consists of *i)* method, technique, or approach, *ii)* model, architecture, or framework, and *iii)* tool. A tool can be:

- *Proprietary:* A tool that is not commercially available but there is a party that has the right to grant a license for using it.
- *Freely available:* Open for all users.
- *Commercial:* This tool has a commercial purpose but licence might be needed in order to use it or it can be open-source depending on developers' decision.

### Maturity level

Maturity level of a study is described based on maturity classification according to the Redwine-Riddle maturity model [58]. Accordingly, Score 1 means "not mature at all", so the study only presents the basic ideas but there is no proof of concept. Score 2 means "somewhat mature", the study provides a proof of concept, and the contribution is also demonstrated on use cases. The highest is a score 3, which means "mature", the study includes the proof of concept and the usability presented on one or more use cases. Furthermore, there is evidence of the usage of the contribution by the research community. Score 0 means "inconclusive", the contribution of the study can not be classified as any of the above ones.

## 5.3.2 Purpose

The second top-level category in the data extraction form is denoted by “purpose". This category classifies the primary studies according to the purpose of the contribution. We identify three main purposes of the contributions in the area: *i)* to **optimize** specific aspects of a technique, *ii)* to **design** a new technique or an architecture, and *iii)* to **evaluate** a current technique or architecture as depicted in Figure 5.5.

### Optimization

The optimization refers to the end-to-end schedule optimization [59] or cost optimization. End-to-end schedule optimization considers the following parameters:

- *Latency:* measures the time it takes for data to propagate from its source node to its destination node via the network.

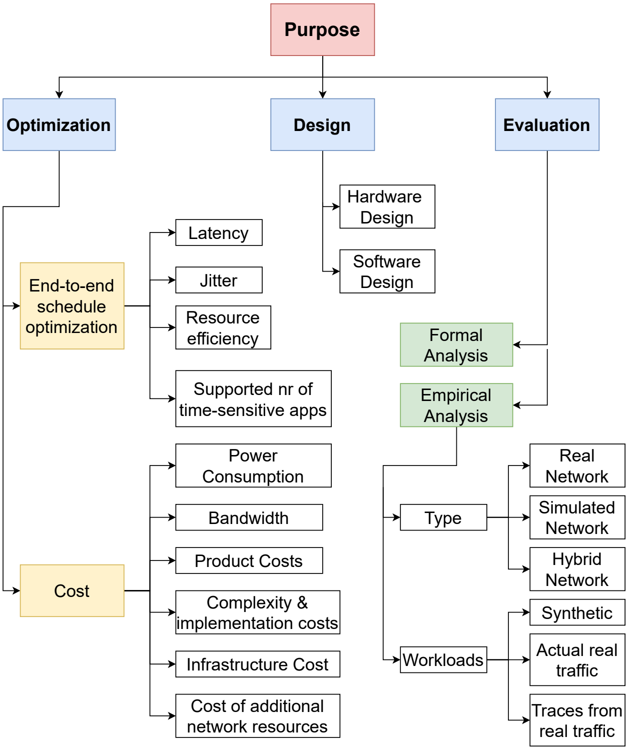


**Figure 5.5:** Data extraction form, considering different purposes of each primary study.

- *Jitter:* a variation in delay usually caused by network congestion.
- *Resource efficiency:* addressed in some of the primary studies which aim to achieve an improved schedule of the network.
- *Supported number of time-sensitive applications:* affects the timing requirements and overall performance of the network.

Cost is a broad aspect of optimization, which can be further categorized as follows:

- Power Consumption
- Bandwidth
- Product Costs
- Complexity and implementation costs

- Infrastructure cost
- Cost of additional network resources

#### Design

The purpose of a primary study could be to develop a technique or a method for designing an architecture or a prototype of a TSN-5G integrated system. The designed prototype could represent, for example, a hardware and/or software for the network interface that supports connectivity, synchronization, scheduling, and analysis of TSN-5G integration.

#### Evaluation

The purpose of a primary study could also be to evaluate a technique or a method for TSN-5G integration using formal and/or empirical analysis. The analysis can be performed on a real network, simulated network, or hybrid network. Furthermore, the workloads used for the evaluation could be (i) synthetically generated, (ii) acquired from real network traffic, or (iii) based on the traces generated by running real traffic.

### 5.3.3 Domain

The third top-level category in the data extraction represents the application domain of the research contribution presented in each primary study. The proposed contribution in a primary study could be applicable generally or proposed for a specific domain or a particular segment of the industry, e.g., industrial automation [60, 61], automotive [62–64], railways, avionics, etc.

### 5.3.4 Research type

The general taxonomy of classifying research studies based on their research type is summarized in [65]. To classify the research type in the primary studies, we use a reduced classification of the general taxonomy as presented in [66]. We classify the primary studies using the following research types.

I. *Solution Proposal* - This type of research proposes a new technique or an extension of an existing technique and discusses its relevance. Small examples, a sound argument or other means may be used to provide a proof of concept of the proposed/extended technique.

II. *Validation Research* - This type of research aims at investigating some properties of a solution proposal and presenting a novel technique or method that is not yet implemented in practice. The investigation is conducted systematically utilizing various activities, including the development of prototypes, performing simulations, conducting experiments, performing mathematical analysis, and mathematically proving the properties.

III. *Conceptual (Philosophical) Proposal* - This type of research proposes a new conceptual framework. Furthermore, using the framework provides a new way of looking at the problem at hand.

IV. *Evaluation research* - This type of research evaluates an implemented solution in practice (real environment). The evaluation is often conducted by means of case studies, field studies, or field experiments.

V. *Experience paper* - This type of research presents the lessons learned by the researchers from their own experience of solving the research problem. These kinds of studies are performed by researchers who have used some tools in practice or by industry practitioners who report their experience of studying the problem in industrial settings.

## 5.4 Results: Vertical Analysis

We follow the data analysis guidelines provided by Cruzes and Dyba [67] to perform the vertical and horizontal analyses of the extracted data that we gathered in this study. The vertical analysis, performed in this section, is used to find information about each of the categories identified in the data extraction form. As the first step, we analyze each primary study specifying the parameters that the extraction form requests, and then we analyze the entire pool of primary studies to find any potential gap in the existing research. Note that we also provide summary tables (Tables 5.2-5.13) where each primary study is connected to each specific category and its characterizing value(s). The references identified with blue-color text are common between two different categories.

On the other hand, horizontal analysis (presented in the next section) is used to identify the possible relations between two different categories, showing the trends and potential gaps through contingency tables.

This section provides an analysis of each of the categories of our data extraction form and answers our first and second research questions. We access trends and venues of primary studies over time. Furthermore, we investigate the existing approaches and techniques for TSN-5G integration in terms of their technical characteristics. The selected set of primary studies is presented in Table 5.2. This table categorizes the primary studies based on the technical contributions specified in Figure 5.4. We choose this special category as it includes all the set of primary studies considering our goal to focus particularly on TSN-5G integration.

**Table 5.2:** Categorization and tabulation of primary studies based on the technical contributions.

| **Technical category** | **Reference to the paper** |
|---|---|
| Resource Management | [23], [24], [25], [60], [61], [62], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], [79], [80], [81], [82], [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [102], [103], [104], [105], [106], [107], [108], [109], [110], [111] |
| Flow Management | [23], [24], [60], [61], [68], [69], [70], [71], [73], [74], [75], [76], [78], [79], [81], [82], [83], [84], [85], [96], [98], [99], [112], [113], [114], [107], [108], [110] |
| Time Synchronization | [23], [24], [25], [61], [62], [68], [69], [70], [71], [74], [75], [76], [78], [79], [81], [83], [84], [85], [87], [88], [89], [90], [91], [93], [94], [97], [98], [100], [102], [104], [105], [112], [113], [115], [116], [117], [118], [119], [120], [121], [122], [123], [124], [125], [126], [127], [128], [129], [130], [131], [132], [133], [106], [107], [108], [134], [111], [135], [136], [137] |
| Integration Architecture | [23], [24], [25], [60], [61], [62], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], [79], [80], [81], [82], [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [102], [103], [104], [105], [112], [113], [115], [116], [117], [118], [119], [120], [121], [122], [123], [124], [125], [126], [127], [128], [129], [130], [131], [138], [139], [140], [132], [133], [141], [106], [114], [107], [108], [134], [109], [110], [111], [135], [136], [142], [143], [137] |

In the following subsections, we provide an answer to our first research question: *RQ1: What are the technical characteristics of TSN and 5G integration?*

### 5.4.1 Analysis based on technical contributions

In this subsection, we investigate the set of primary studies based on their technical contributions to the research area. Based on our classification scheme, we analyze the technical contributions of the studies based on the aspects they address, which can be resource management, flow management, time synchronization, and integration architecture, as shown in Figure 5.6. A summary table of the primary studies belonging to each technical category was presented earlier in Table 5.2.

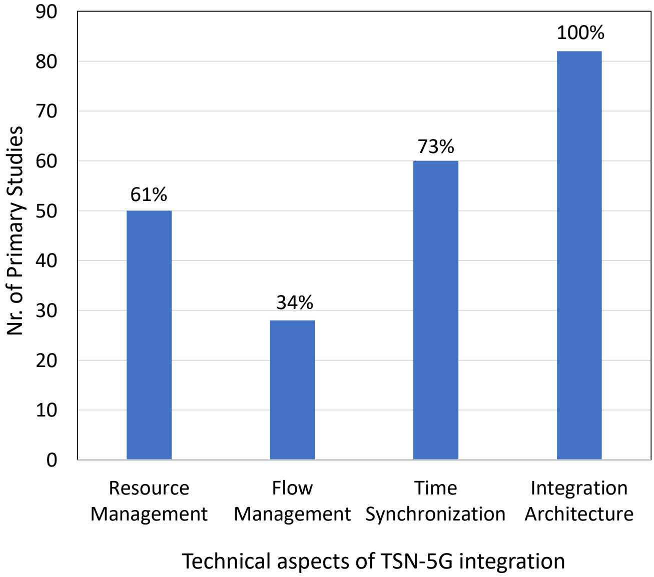


**Figure 5.6:** Number of primary studies providing various technical contributions for TSN-5G integration.

We notice that 73% of the primary studies address the time synchronization, which is actually a significant challenge for the integration of TSN and 5G technologies. 60 primary studies focus on time synchronization of TSN and 5G. The majority of the primary studies propose a synchronized approach with an accuracy starting from the levels of hundred nanoseconds to one microsecond. There are six primary studies [81,85,87,98,103,121] that do not consider time synchronization, but rather propose non-synchronized solutions for TSN and 5G integration. Usually, the choice of synchronized or non-synchronized solution depends on the specific requirements of the system. Clock synchronization is a critical aspect in real-time systems, where the timing of events and the order in which they occur can have significant consequences.

The majority of the primary studies (34) that address time-synchronization use the transparent clock approach that utilizes the Precision Time Protocol (PTP). Whereas, there are only two primary studies that use the boundary approach as shown in Table 5.3.

**Table 5.3:** A summary of primary studies according to the approach they use to achieve the time synchronization.

| Time synchronization approach | Reference to the paper |
|---|---|
| Transparent Clock Approach | [25], [113], [71], [115], [24], [116], [62], [117], [118], [79], [120], [123], [124], [126], [127], [128], [93], [94], [97], [100], [132], [133], [102], [104], [106], [83], [129], [88], [91], [131], [122], [111], [135], [137] |
| Boundary Clock Approach | [23], [125] |

The transparent clock approach is usually used in high-precision applications, to maintain a very accurate view of the current time because it takes into account the delays introduced by the network itself. On the other hand, the boundary clock approach is simpler to implement and maintain, but it is less accurate as it depends on the accuracy of the clocks at the boundary of each subnetwork, which may not be as precise as more central clocks. Note that both approaches are proposed by the 3GPP standards.

There are 50 primary studies (61% of the total) that provide technical contributions in the context of resource management in TSN-5G integrated systems. Among these studies, 31 use the fully centralized configuration model proposed by the IEEE 802.1 QCC standard (Table 5.4). One advantage of the centralized model compared to the distributed one is that the centralized model can be easily incorporated into the specifications provided by 3GPP to manage and control the TSN-5G network.

**Table 5.4:** A summary of primary studies according to the network configuration model.

| Configuration model | Reference to the paper |
|---|---|
| Fully distributed model | [25] |
| Centralized network/ distributed user model | [23] |
| Fully centralized model | [25], [68], [71], [60], [61], [72], [24], [74], [62], [76], [78], [79], [80], [81], [82], [86], [92], [93], [96], [100], [101], [103], [106], [83], [88], [89], [91], [107], [108], [109], [111] |
| Others | [69], [73], [85] |

On the other hand 23 primary studies focus on providing different scheduling techniques for TSN-5G network. Among the scheduling algorithms semi-persistent scheduling (SPS) is used by the majority of the papers, as shown in Table 5.5. In SPS, a dedicated channel is reserved for a specific user for a predetermined period of time. SPS is a useful technique for supporting the transmission of periodic data with low latency and high reliability in wireless communication systems, however it may not be suitable for traffic that is highly variable or unpredictable in nature, as it may require a more flexible scheduling approach.

**Table 5.5:** A summary of primary studies according to the proposed scheduling technique.

| **Scheduling technique** | **Reference to the paper** |
|---|---|
| Semi-persistent scheduling | [23], [60], [24], [76], [77], [99], [100] |
| Configured grant scheduling | [71], [60], [100] |
| Dynamic scheduling | [68] |
| Window-based scheduling | [86] |
| Others | [61], [72], [74], [75], [118], [84], [85], [95], [102], [106], [108], [109], [110], [111] |

The analysis of the primary studies also reveals that 74% of these studies (representing % of all studies) contribute towards the integration architectures for TSN and 5G that conform to the 3GPP specifications (Release 15, 16, 17 or others as shown in Figure 5.7). Whereas, the TSN-5G integration architectures addressed in the remaining primary studies (26% of the total number of primary studies) do not comply with any of the 3GPP Releases [68–70, 72, 80, 84, 85, 95–99, 110, 121, 124, 130, 132–134, 136, 142].

In addition, the number of primary studies addressing each property of the TSN-5G integration architecture is depicted in Figure 5.8, while a summary table of the primary studies belonging to each integration architecture property is presented in Table 5.6. Overall, dependability is an essential requirements for TSN-5G network as it enables the transmission of time-critical data with low latency and high reliability. TSN networks need to be secure in order to prevent unauthorized access to the critical data. Ensuring the security of TSN in a 5G environment is one of the major challenges, as it requires the integration of multiple security technologies. On the other hand, interoperability is also a challenge, as TSN and 5G components may use different protocols and technologies. It should be noted that one of the challenges of TSN-5G integration comes from the standardization. TSN is still an evolving standard,

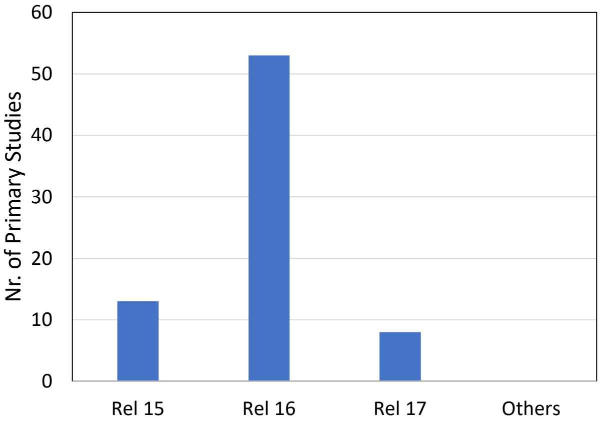


**Figure 5.7:** Number of primary studies conforming to various releases of the 3GPP specification.

and this can lead to challenges in terms of interoperability and compatibility as there might be ongoing efforts to standardize TSN-5G integration.

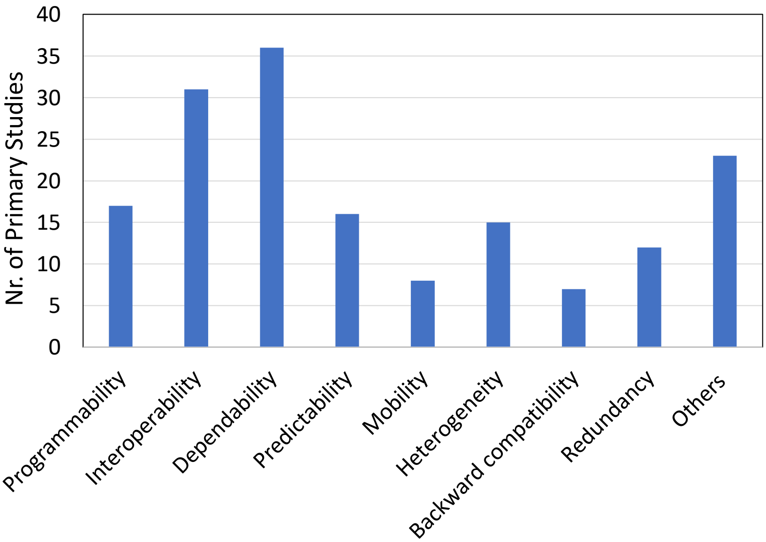


**Figure 5.8:** Number of primary studies addressing various properties of integration architectures for TSN and 5G.

**Table 5.6:** A summary of primary studies according to the properties of integration architectures for TSN and 5G. Note that the references identified with blue text are common between two different categories.

| **Architecture's properties** | **Reference to the paper** |
|---|---|
| Programmability | [24], [60], [61], [68], [69], [72], [73], [85], [86], [87], [92], [98], [103], [132], [110], [108], [136] |
| Interoperability | [23], [24], [60], [61], [68], [72], [74], [81], [82], [83], [88], [89], [92], [95], [96], [100], [101], [102], [103], [104], [119], [120], [121], [138], [141], [106], [114], [107], [108], [111], [142], |
| Dependability | [23], [61], [68], [76], [81], [82], [83], [84], [86], [89], [90], [91], [93], [96], [98], [99], [100], [102], [112], [118], [120], [128], [129], [131], [132], [133], [138], [139], [140], [106], [134], [109], [110], [135], [143] |
| Predictability | [23], [24], [60], [61], [69], [76], [80], [102], [115], [116], [117], [122], [139], [108], [136], [137] |
| Mobility | [24], [70], [62], [76], [78], [79], [113], [139] |
| Heterogeneity | [68], [70], [72], [73], [74], [82], [85], [84], [92], [99], [101], [105], [139], [114], [108] |
| Backward Compatibility | [82], [87], [88], [93], [103], [116], [121] |
| Redundancy | [23], [24], [25], [61], [68], [71], [78], [81], [84], [118], [119], [134], |
| Others | [25], [75], [77], [81], [91], [93], [94], [97], [98], [99], [123], [124], [125], [126], [127], [128], [129], [130], [131], [132], [133], [141], [135] |

### 5.4.2 Analysis based on the contribution type

In this subsection, we discuss the distribution of the primary studies considering their type of contribution as presented earlier in Section 5.3.1. Figure 5.9 presents the number of primary studies addressing each contribution type. It can be observed that 37 primary studies focus on providing a method, technique, or approach for TSN-5G integration. Similarly, a set of 27 primary studies provide a model, architecture, or framework for TSN-5G integration.

It is interesting to note that none of the primary studies have provided a tool as a contribution (Table 5.7). Often, tools are the means to transfer scientific results to the industry. This indicates that there is an urgent need for provisioning of tools that incorporate the existing techniques or new techniques for

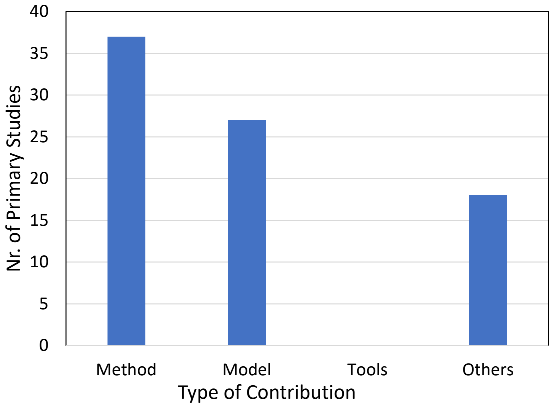


**Figure 5.9:** Number of primary studies providing the type of contribution with regards to TSN-5G integration.

TSN-5G integration. The remaining 18 primary studies provide other contributions, e.g, to provide options for TSN and 5G, to investigate the impact and derive requirements on the end-to-end system, to present the key technologies, challenges, and research directions.

**Table 5.7:** A summary of primary studies according to the type of contribution with regard to TSN-5G integration.

| **Type of contribution** | **Reference to the paper** |
|---|---|
| Method | [25], [62], [71], [73], [74], [80], [85], [86], [92], [93], [94], [97], [100], [101], [103], [104], [112], [115], [116], [117], [118], [120], [121], [122], [123], [124], [126], [127], [128], [130], [140], [114], [109], [110], [135], [142], [137] |
| Model | [23], [60], [68], [69], [70], [72], [76], [78], [79], [81], [82], [84], [91], [95], [96], [98], [99], [102], [113], [119], [125], [132], [133], [138], [108], [136], [143] |
| Tool | - |
| Others | [24], [61], [75], [77], [83], [87], [88], [89], [90], [105], [129], [131], [139], [141], [106], [107], [134], [111] |

### 5.4.3 Analysis based on the research type

There are 5 research types that we presented as part of the data extraction form: (i) solution proposal, (ii) validation research, (iii) conceptual (philosophical) proposal, (iv) evaluation research, and (v) experience paper. We identify that 42 primary studies provide validation research for TSN-5G integration. Similarly, 35 primary studies present solution proposals for the integration of TSN and 5G as shown in Figure 5.10. These studies develop proof-of-concept prototypes and perform simulations and mathematical analysis using the prototypes. Only 5 primary studies provide conceptual proposal for TSN-5G integration. It is interesting to note that none of the primary studies provide evaluation research or experience papers (Table 5.8). This analysis identifies a gap in the research types in this area, which is also an indicator of the immature nature of TSN-5G research.

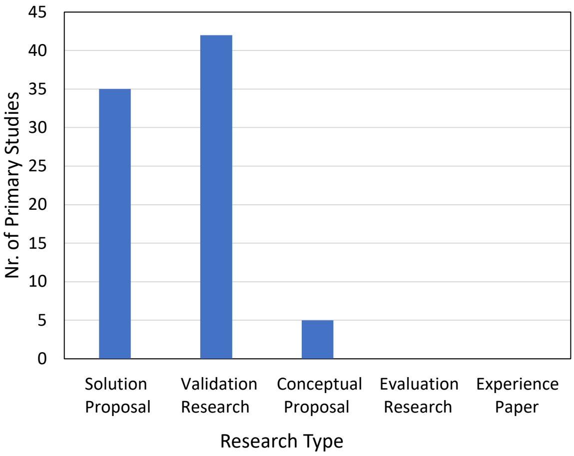


**Figure 5.10:** Distribution of primary studies according to research type classification.

### 5.4.4 Analysis based on the maturity level

In this subsection, we analyze the primary studies with respect to the maturity levels according to the Redwine-Riddle maturity model [58], also described in Section 5.3.1. According to this model, we classify the primary studies using one of the scores: 0, 1, 2, or 3 representing “inconclusive", “not mature at all", “somewhat mature" or “mature" respectively. It can be observed in Figure 5.11 that 55% of all primary studies are somewhat mature as the technical contributions in these studies have been demonstrated in use cases involving TSN-5G

**Table 5.8:** A summary of primary studies according to research type classification.

| **Research type** | **Reference to the paper** |
|---|---|
| Solution Proposal | [24], [25], [60], [62], [68], [70], [71], [72], [73], [75], [76], [79], [83], [88], [89], [90], [93], [94], [96], [100], [112], [116], [120], [121], [124], [129], [130], [138], [139], [106], [108], [135], [136], [143] |
| Validation Research | [23], [61], [69], [74], [77], [78], [80], [81], [82], [84], [85], [86], [87], [92], [95], [97], [98], [99], [113], [115], [117], [118], [119], [122], [123], [125], [126], [127], [128], [140], [132], [133], [101], [102], [103], [104], [134], [109], [110], [111], [142], [137] |
| Conceptual Proposal | [91], [105], [131], [141], [107] |
| Evaluation Research | - |
| Experience Paper | - |

integration. Whereas, 43% of all primary studies are not mature at all as they only present basic ideas without providing any proof of concept for TSN-5G integration. It is interesting to note that only two of the primary studies are mature according to the Redwine-Riddle maturity model.

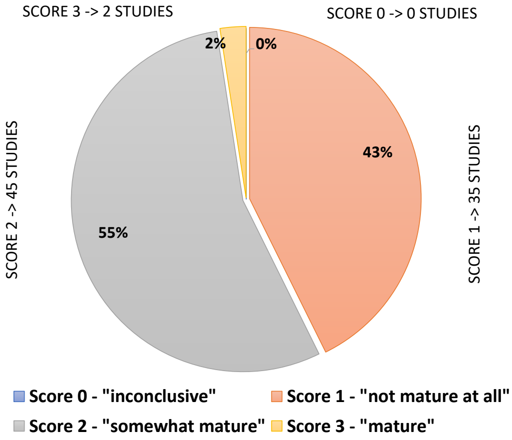


**Figure 5.11:** Distribution of primary studies according to the maturity level of their contributions with regard to TSN-5G integration.

### 5.4.5 Analysis based on the purpose of contributions

In this subsection, we analyze each primary study based on the purpose of the contribution as discussed in Section 5.3.2. Figure 5.12 presents the number of primary studies that aim at evaluating, designing, or optimizing some techniques for TSN and 5G integration. We notice that a large majority of the primary studies (70) focus on optimizing the TSN-5G integrated systems. Furthermore, 68 primary studies focus on design, whereas 57 primary studies provide an evaluation of the techniques for TSN-5G systems. Note that several primary studies have more than one purpose in the proposed contributions, e.g., to design and evaluate, to design and optimize, or to optimize and evaluate.

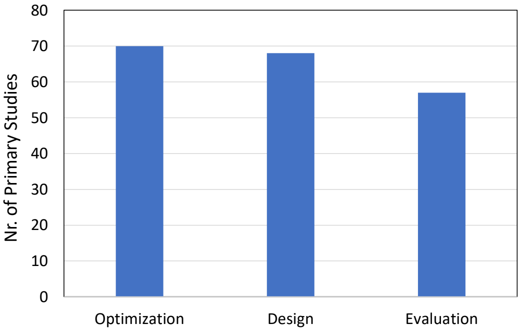


**Figure 5.12:** Number of primary studies according to the purpose of contribution in the context of TSN-5G integration.

#### Purpose of contribution – optimization

If the purpose of contribution in a primary study is to perform optimization, then we identified two sub-categories in our data-extraction form: end-to-end schedule optimization and cost optimization. Figure 5.13 shows that 74% of the primary studies aim at optimizing latency, which is a key quality-of-service attribute in many applications in various domains, e.g., Industrial Internet of Things (IIoT). Achieving TSN low latencies in a 5G network may be challenging due to the high traffic volumes and potential interference from other devices.

The second most commonly addressed attributes are jitter, and resource efficiency, which are subject to optimization by 24% and 23% of the primary studies respectively. TSN can contribute to resource efficiency in 5G networks by its ability to support fine-grained, deterministic scheduling of network resources. This allows TSN to allocate network resources in a precise and predictable manner, optimizing the use of network resources and reducing congestion. Furthermore, 7% of the primary studies focus on the optimization of additional resources like the supported number of time-sensitive and/or background applications. Overall, 5G networks are designed to support a wide range of applications and services with different set of requirements, including high data rates, low latency, and high reliability.

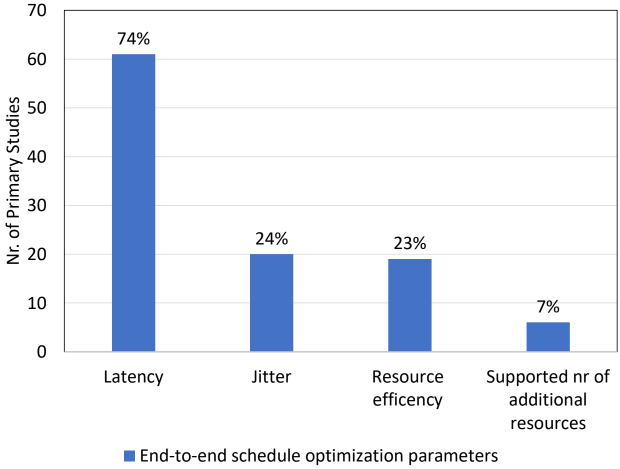


**Figure 5.13:** Number of primary studies addressing various attributes for end-to-end schedule optimization in TSN-5G systems.

Many primary studies also address optimization of various types of costs in the context of TSN-5G integration as shown in Figure 5.14. Optimization of bandwidth cost in TSN-5G integration is the most studied topic, which is addressed by 14 primary studies. Furthermore, optimization of the costs of “Complexity and implementation", “infrastructure", and “cost of additional network resources" in TSN-5G integrated systems are addressed by 6 primary studies each. Similarly, a few studies have also addressed optimization of product costs, power consumption, and other resources (e.g., flow acceptance ratio) in TSN-5G integrated systems as shown in Figure 5.14. Implementing TSN-5G networks can be expensive, as it requires the deployment of additional hardware and software. Note that some primary studies address optimization of more than one type of costs (Table 5.10).

**Table 5.9:** A summary of primary studies according to various attributes for end-to-end schedule optimization in TSN-5G systems.

| **Scheduling Parameter** | **Reference to the paper** |
|---|---|
| Latency | [23], [24], [60], [61], [62], [68], [69], [70], [71], [72], [74], [75], [76], [78], [80], [82], [84], [87], [88], [89], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [102], [104], [112], [116], [118], [119], [120], [121], [122], [125], [127], [128], [129], [130], [132], [133], [138], [139], [140], [141], [106], [114], [108], [134], [109], [110], [111], [136], [142], [143], [137] |
| Jitter | [61], [68], [69], [74], [76], [80], [82], [99], [102], [113], [115], [118], [132], [133], [138], [106], [114], [108], [134], [136] |
| Resource Efficiency | [23], [68], [71], [73], [74], [76], [77], [78], [85], [86], [92], [93], [97], [98], [99], [100], [114], [109], [110] |
| Supported number of additional resources | [61], [74], [77], [87], [115], [121] |

**Table 5.10:** A summary of primary studies according to various types of cost optimization in TSN-5G systems.

| **Type of cost** | **Reference to the paper** |
|---|---|
| Power Consumption | [24], [68], [69], [139] |
| Bandwidth | [23], [69], [70], [73], [82], [86], [98], [118], [121], [138], [114], [109], [142], [143] |
| Product Cost | [98], [139] |
| Complexity and Implementation | [61], [62], [73], [78], [82], [112] |
| Infrastructure | [69], [72], [82], [105], [115], [108] |
| Cost of Additional Network Resources | [73], [84], [85], [86], [92], [110] |
| Others | [81], [123] |

### Purpose of contribution – design

We identified that 72% (59 studies) of all the primary studies provide software design for the technique to integrate the TSN and 5G technologies. Fur-

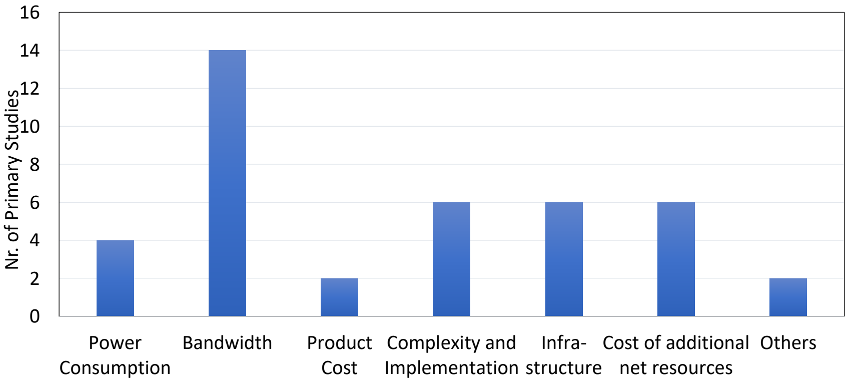


**Figure 5.14:** Number of primary studies addressing various types of cost optimization in TSN-5G integrated systems.

thermore, we observe that only 12 primary studies (15% of the total) present hardware design for the TSN and 5G integration. We also note that only three primary studies [103, 130, 138] (Table 5.11) addresses both the software and hardware design of the suggested approach for TSN-5G integration. TSN-5G hardware devices need to have certain capabilities including support for IEEE 802.1 standards, clock synchronization, QoS mechanisms such as packet classification, scheduling, and traffic shaping, etc. Overall, the hardware design of TSN-enabled devices in a 5G network will depend on the specific requirements of the application, however it may take some time before TSN-5G devices become widely available on the market.

**Table 5.11:** A summary of primary studies according to the type of design of TSN-5G integrated systems.

| **Type of design** | **Reference to the paper** |
|---|---|
| Software Design | [23], [24], [25], [61], [62], [68], [71], [74], [75], [76], [77], [79], [80], [81], [82], [83], [84], [85], [86], [87], [90], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [103], [112], [115], [116], [117], [118], [120], [122], [123], [124], [125], [126], [127], [128], [130], [138], [139], [141], [132], [133], [114], [107], [108], [109], [110], [135], [136], [142] |
| Hardware Design | [60], [69], [87], [102], [103], [119], [121], [130], [131], [138], [134], [111] |

### Purpose of contribution – evaluation

We observe that a large majority of the primary studies (49 studies) use empirical evaluation for the proposed technical contributions. On the other hand, 20 primary studies use formal analysis to evaluate the proposed technique(s) for TSN-5G integration. Figure 5.15 shows the number of primary studies per evaluation setup. The empirical analysis is mostly used in our set of primary studies (Table 5.12), assuming mostly a simulated network in N3, OMNeT++, or other simulation tools using synthetically generated workloads. These tools include a TSN module, as well as a 5G module to simulate TSN-5G networks. The choice of the simulation tool will depend on the specific requirements and goals of the simulation.

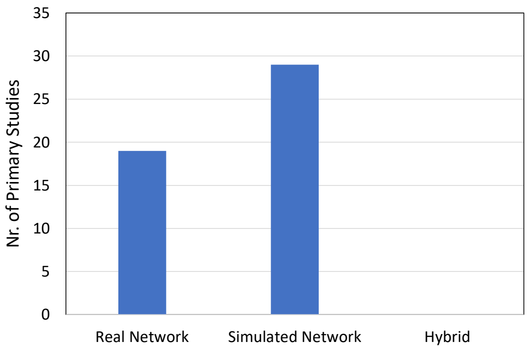
The majority of the primary studies (29 studies) use simulated networks for their empirical evaluation, while 19 studies use a real network to perform the evaluation of their TSN-5G suggested technique/approach as shown in Figure 15(a). We note that there are no publications of type hybrid, considering an integration between real hardware and simulated network components. Another part of the empirical evaluation is the type of workload used in the evaluation set up as shown in Figure 15(b). We notice that the majority of primary studies (24 studies) use a workload of type synthetic, while there are six primary studies having actual real traffic on their evaluation set up, and two primary study using traces from real traffic. Considering the immature nature of TSN-5G networks, it is hard for the researchers to test and evaluate their approaches using real traffic from an established TSN-5G network.

## 5.4.6 Analysis based on the domain

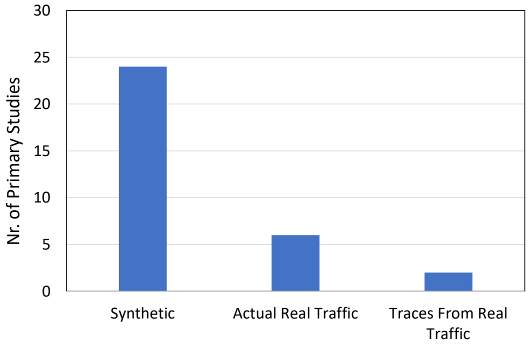
The domain where a technique or framework is applied can be generic, or specific depending on the focused area. As shown in Table 5.13, 55 primary studies (67% of the total) provide domain-agnostic techniques for the integration of TSN and 5G technologies. There are 22 primary studies (24% of the total) that are focused on the industrial automation domain. There are only three primary studies that focus on the automotive domain. The research on TSN-5G integration is still in its early stages which explains the large number of primary studies that have no concrete application domain in focus.

## 5.4.7 Publication trends

This subsection presents the publication trends based on the extracted data from the primary studies, thereby addressing the second research question: *RQ2: What are the publication trends of TSN and 5G integration?* To answer



**(a)** Distribution of primary studies based on the type of empirical evaluation.



**(b)** Distribution of primary studies based on the type of workload used for the empirical evaluation set up.

**Figure 5.15:** Empirical evaluation strategies used by the primary studies.

this question, we extract the year of publication and venue from each primary study.

**Publication year.** As shown in Figure 5.16, publications in this research area commenced in 2018 after the initial delivery of 3GPP Release 15 in late 2017, which was the first full set of 5G standards. This shows that the research area is still in its infancy. The number of primary studies started to increase in 2019, 2020, and 2021 with 10, 24 and 26 publications respectively. The results also show that the interest of researchers in the area is continuously growing.

**Publication venues.** We analyze the primary studies based on the publication type, which can be a journal, a conference, a workshop, or a book chapter. The results reveal that most of the primary studies (47 out of 82) are published in conferences. 24 primary studies are published in journals with at least 3 journal

**Table 5.12:** A summary of primary studies according to the empirical evaluation strategies.

| Empirical Evaluation | | Reference to the paper |
|---|---|---|
| Type of Evaluation | Real Network | [23], [60], [72], [82], [87], [102], [103], [104] [116], [118], [119], [121], [132], [133], [138], [134], [111], [136], [137] |
| | Simulated Network | [23], [61], [69], [70], [77], [80], [81], [84], [85], [86], [92], [95], [96], [97], [98], [99], [101], [113], [115], [117], [120], [106], [122], [127], [140], [108], [109], [110], [142] |
| | Hybrid | - |
| Type of Workload | Synthetic | [61], [69], [71], [74], [81], [82], [84], [85], [86], [87], [95] [113], [115], [106], [121], [122], [127], [134], [136], [137], [108], [109], [110], [142] |
| | Actual Real Traffic | [23], [102], [103], [104], [138], [111] |
| | Traces from Real Traffic | [98], [116] |

**Table 5.13:** Number of primary studies per each type of domain.

| Type of domain | Number of Primary Studies | Reference to paper |
|---|---|---|
| Generic | 55 | [23], [25], [68], [69], [70], [71], [72], [73], [74], [75], [77], [79], [81], [82], [85], [86], [87], [88], [91], [92], [93], [94], [95], [96], [97], [99], [100], [103], [104], [105], [112], [113], [115], [117], [118], [121], [122], [123], [124], [125], [126], [127], [128], [129], [130], [131], [132], [133], [140], [141], [107], [110], [135], [136], [137] |
| Industrial Automation | 22 | [24], [60], [61], [76], [78], [80], [83], [89], [90], [98], [102], [116], [120], [130], [138], [139], [108], [134], [109], [111], [143], [106] |
| Automotive | 3 | [62], [101], [142] |
| Smart Cities | 1 | [119] |
| Medical | 1 | [84] |

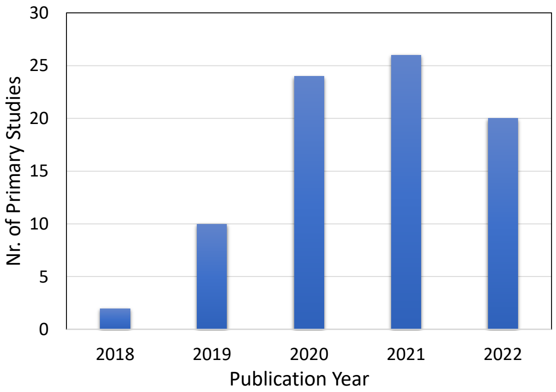


**Figure 5.16:** Publication trend in the research on TSN-5G integration.

publications per year since 2019, 1 primary study is a book chapter, while the remaining primary studies are part of our grey literature search consisting of white papers, web pages, or forums.

Another classification is based on the targeted publication venues. In Table 5.14, we list the publication venues where at least two primary studies have been published. The IEEE International Workshop on Factory Communication Systems (WFCS) and the IEEE International Conference on Emerging Technologies and Factory Automation (ETFA) have published the highest number of primary studies to date.

**Table 5.14:** Publication venues with at least 2 primary studies.

| **Venue name** | **Acronym** | **Type** | **#papers** |
|---|---|---|---|
| IEEE International Workshop on Factory Communication Systems | WFCS | C | 6 |
| IEEE International Conference on Emerging Technologies and Factory Automation | ETFA | C | 6 |
| IEEE Communications Standards Magazine | - | J | 5 |
| IEEE Network | - | J | 3 |
| IEEE Access | - | J | 3 |
| IEEE International Conference on Edge Computing | EDGE | C | 2 |
| International Conference on Information and Communication Technology Convergence | ICTC | C | 2 |
| IEEE International Conference on Communications | ICC | C | 2 |

## 5.5 Results: Horizontal Analysis

In this section, we investigate the possible relations that might exist between different categories of the data extracted from the primary studies. The purpose of this analysis is to highlight the main focus and identify the potential gaps in the existing research on the integration of TSN and 5G technologies. This analysis aims to provide an answer to the third research question, *RQ3: What are the limitations of TSN-5G integration?*

We analyze the relationship between two different categories using bubble plots in which the size of the bubble corresponds to the number of primary studies addressing the pair of categories intersecting each other. The first bubble plot, depicted in Figure 5.17, shows the relationship between the technical contribution classification (along the vertical axis) and the research type classification (along the horizontal axis). As can be noticed from the plot, the majority of the existing research in the area is focused on presenting solution proposals and validation research for TSN-5G integration techniques. 35 primary studies provide solution proposals for TSN-5G integration architectures. Furthermore, there are 26, 14, and 22 primary studies that provide solution proposals for time synchronization, flow management, and resource management in the context of TSN-5G integration respectively. Similarly, there are 42, 25, 12 and 23 primary studies that present validation research for integration architectures, time synchronization, flow management, and resource management respectively. In addition, there are a few primary studies that present a conceptual proposal for TSN-5G integration. It can be observed in Figure 5.17 that there are no evaluation research and experience papers that provide a technical contribution (integration architectures, time synchronization, flow management, and resource management) for TSN-5G integration. This identifies a potential gap in the existing research and provides opportunities for further research on the integration of TSN and 5G technologies.

The relationship between the technical contribution classification and the contribution type classification in the primary studies is illustrated by the bubble chart in Figure 5.18. It can be observed from the bubble chart that the majority of primary studies provide a method/technique/approach or a model/framework/architecture for the integration of TSN and 5G technologies. For instance, there are 37, 26, 7, and 17 primary studies on TSN-5G integration that provide a method, a technique, or an approach for the integration architectures, time synchronization, flow management, and resource management respectively. Similarly, there are 27, 17, 16, and 19 primary studies on the integration of TSN and 5G technologies that provide a model, an architecture or a framework to support the integration architectures, time synchronization, flow

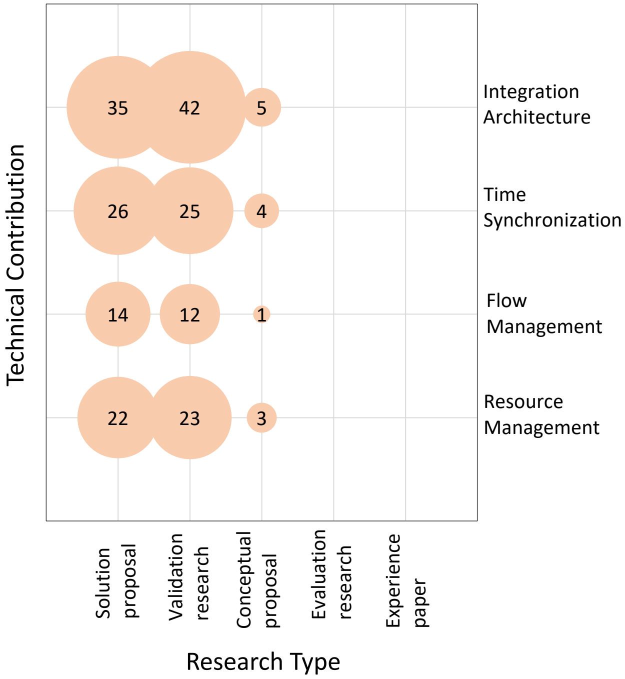


**Figure 5.17:** Relationship between the research type and technical contribution classifications in the primary studies.

management, and resource management, respectively. Integration architecture is addressed in most of the primary and this can be motivated by the converged nature of a new network which still needs a lot of research and investigation.

The bubble chart in Figure 5.18 also indicates that there are a few primary studies that provide other types of contribution with regards to the TSN-5G integration architecture, time synchronization, flow management, and resource management, e.g., solutions for TSN on 5G fronthaul [75]. One major gap that we identify in the existing research on the TSN-5G integration is that there is no tool support available with any of the proposed techniques. This is evident from zero entries in the “Tools" column in Figure 5.18. Note that tools serve as a vehicle to transfer research results from academia to industry. This calls for the research community to develop prototypes of a tool that implements the scientific techniques for the integration of TSN and 5G technologies.

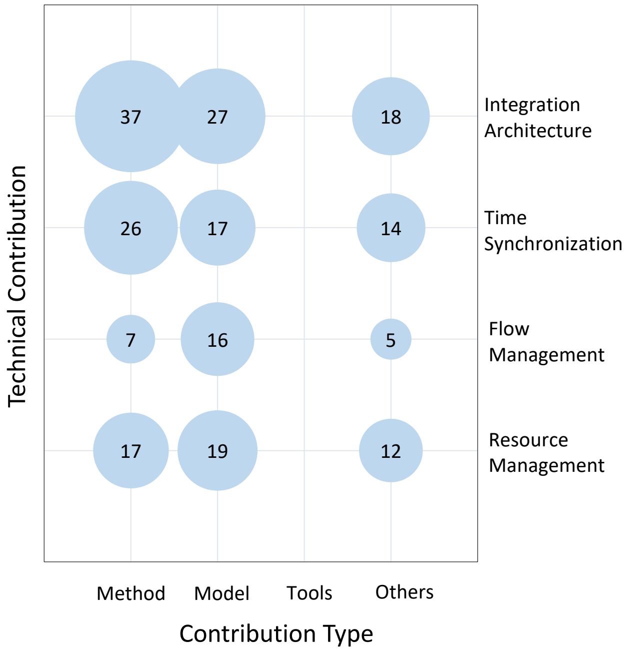


**Figure 5.18:** Relationship between the technical contribution and contribution type classifications in the primary studies.

## 5.6 Fleiss Kappa Analysis

Fleiss kappa is a statistical analysis that can help in defining the level of agreement among the researchers during the selection phase of this systematic literature review. We will use it to address the possible threats to validity and to ensure the reliability of our study inclusion decisions.

The idea of such statistical analysis came firstly from Cohen [144] who considered a case when two raters were trying to rate or categorize a set of subjects. He introduced a kappa value to measure the level of agreement between two raters. Fleiss kappa statistical analysis [145] was introduced to eliminate the limitation of only two raters. We use this method in the early phase of the selection of publications to access the reliability of agreement among the researchers performing this study.

To perform the Fleiss Kappa analysis, three researchers were assigned 25 publications each. The publications were selected randomly from the search pool of publications taken after the removal of duplicates and impurities as shown in Figure 5.2. The researchers independently categorize those publications as Relevant, Not Relevant, or Not Clear based on title, abstract, keywords, and full-text skimming (if needed). From the Fleiss Kappa point of view, the 25 papers are the subjects that need to be categorized by the 3 raters into 3 categories. **After applying the analysis, we calculated the overall agreement among the researchers on a value of 83% which indicates a strong level of agreement among the raters** [146]. Based on this statistical analysis we conclude that the researchers had a strong level of agreement when selecting the relevant papers for the systematic literature review.

## 5.7 Threats to Validity

To prove the quality of our study, we discuss in detail the possible threats to validity and how we managed to mitigate them. There are three types of threats we address: external, internal, and construct validity.

### 5.7.1 External validity

The external threat to validity deals with the generalisability of the results [147]. A possible threat can be a set of selected studies that cannot fully represent the state of the art on TSN-5G integration. To mitigate this potential threat, we make sure to choose multiple data sources which are four of the largest and most complete databases in computer science, computer engineering, software engineering, and systems engineering: ACM Digital Library, IEEEXplore Digital Library, Scopus and Web of Science. After the automatic search, we implement the recursive backward and forward snowballing strategy to be sure about the coverage of our study.

Considering the pilot studies in our systematic literature review, we apply well-defined and constructed inclusion and exclusion criteria. Excluding the studies which are not written in English can be a possible threat, but considering the fact that English is the de-facto language for all the scientific papers, this threat can be omitted.

### 5.7.2 Internal validity

Internal validity refers to the inaccurate settings or variables that may cause a negative impact on the design of our systematic literature review. We mitigated this threat by following well-established guidelines when defining the data extraction form and the process which we follow in this study. Furthermore, we cross-analyzed all the parameters in the data extraction form to identify and solve any potential issues with the consistency of the extracted data.

### 5.7.3 Construct validity

Construct validity refers to the representativeness of the selected studies [22]. The recursive backward and forward snowballing makes us confident on the coverage of our study that we did not miss any relevant study.

In the beginning, we collected the research studies using the search string. The definition of the string can be a potential threat to validity. All the researchers involved in this study discussed together every parameter of the search string by following a rigorous process. This minimizes the threat to construct validity. After the automatic search, studies were analyzed by well-documented inclusion and exclusion criteria. To prove the reliability of the review, three of the researchers independently classified a set of common studies and applied the Fleiss kappa statistical analyses [145] as described in Section V, achieving a kappa value of 83% which means a strong agreement among the researchers.

### 5.7.4 Conclusion validity

The conclusion validity refers to the relationship between extracted data and obtained findings [147]. We mitigated this potential threat by systematically documenting by using a well-defined process and by providing a replication package that allows replicating each step of the process. The replication package is freely accessible[4]. The definition of the data extraction form can be a potential threat to conclusion validity. To mitigate this threat we (i) let the parameters emerge from the pilot studies and refine the parameters throughout the entire data extraction activity, and (ii) make all the researchers actively involved in the definition of the extraction form as well as in the extraction and analysis of the data.

## 5.8 Related Work

There are a few systematic reviews and surveys conducted in the area of TSN and 5G with a special focus in 3GPP Releases. For example, the study in [148] presents an overview of 3GPP Releases focusing on the extensive enhancements to achieve backward compatibility in the subsequent releases. Similar studies are performed by Jerichow et al. [149], Nwakanma et al. [150], and Atiq et al. [32].

Jerichow et al. [149] present an overview of public networks that are integrated with non-public networks within the scope of the 3GPP Release 16 ar-

---

[4] `https://github.com/zenepe1/TSN-5GReplicationPackage`

chitecture. Furthermore, they also discuss security concepts of 5G non-public networks. Nwakanma et al. [150] review the implementation possibilities and challenges of 3GPP Release 16 in Industrial Internet of Things and mission-critical communications. Atiq et al. [32] comprehensively analyze the recent standardization efforts and developments in IEEE 802.11 and 5G, and present a set of use cases enabled by wireless TSN. The authors provide insights in wireless TSN considering time synchronization between 802.11 or 5G and TSN devices, techniques to achieve reliability requirements, and mapping QoS profiles with the TSN defined traffic.

Jun et al. [151] perform a detailed survey of 3GPP standardization activities to ensure low latency at the network level. Furthermore, they investigate the time-sensitive communication in Release 16 and 17, including the time synchronization in a TSN-5G architecture that conforms to the two Releases. Wollschlaeger et al. [1] also present an overview of the 5G evolution among 3GPP Releases starting with Release 15 and concluding with features expected from Release 17. The ongoing standardization in 3GPP regarding the integration of TSN and 5G systems is also addressed by Striffler et al. [78]. The authors identify open issues that still need to be addressed in terms of time synchronization, session continuity, and scheduling of different traffic streams.

On the other hand, there are several works focused on reviewing TSN and its potential use cases [11, 152–154]. Lo Bello et al. [11] surveys TSN in industrial communication and automation systems while discussing core TSN standards and novel features which make TSN an enabler for several cutting-edge technologies. While Lo Bello et al. [11] remain generic, Samii et al. [153] focus on the automotive domain. They review the TSN standards in light of possible use cases in automotive systems. In addition, Deng et al. [154] also takes the automotive use case as an example to discuss the application of TSN in automobiles. The aim of the article is to provide an overview of recent advances and future trends in real-time Ethernet modeling and design methodologies for AVB and TSN. It surveys the current state of the field and provides references for researchers who are interested in this area. Moreover, Craciunas et al. [152] overviews the scheduling problem arising from time-sensitive network technologies like TTEthernet and TSN. The authors describe the main differences between two technologies, and they also describe the scheduling constraints that enable real-time temporal behavior on the level of individual communication streams. Reviewing the existing surveys on TSN, we observe that none of them is focusing on the converged TSN-5G system.

A comprehensive survey of the IEEE TSN and IETF DetNet standards targeting the support for ultra-low latency (ULL) is presented by Nasrallah et al. [7]. This work provides an in-deep survey of the development of IEEE TSN standards and highlights significant milestones illustrating the shift from Audio Video Bridging (AVB) to TSN. Flow synchronization, flow management, flow control, and flow integrity are some of the addressed aspects of TSN including:

- Generic Precision Time Protocol to accomplish time synchronization of data.
- YANG data models to provide a framework for periodic status reporting and the configuration of bridges.
- Resource Allocation Protocol (RAP) to achieve a distributed TSN Control Model since SRP is restricted to A/V applications having a limited number of SR classes. RAP improves scalability by leveraging the Link-Local Reservation Protocol (LRP) to support all TSN features.
- Gate Control List used for the TSN flow control and IEEE 802.1Qbv Time-Aware Shaper (TAS) which is applicable for ULL requirements when all time-triggered windows are synchronized.

On the other hand, this study also addresses the key components in 5G standards for supporting ULL mechanisms. Some of the surveyed components are the Common Public Radio Interface (CPRI) which provides the specifications for packing and transporting baseband time domain and eCPRI to reduce the effective data rate. In addition, this survey also presents an overview of the main ULL research directions in the 5G wireless access segment and on TSN network. This survey covers the link and network layer latency reduction standards covering studies up to July 2018, while B. Briscoe et al. [155] surveys general techniques for reducing latencies in Internet Protocol (IP) packet networks covering studies up to August 2014.

Furthermore, there is also a systematic review of URLLC (Ultra-Reliable Latency Communication) technology of 3GPP presented in [156]. URLLC is a feature that will be covered by 5G and beyond 5G. This review analyses the URLLC networking trend in wireless and wired communication. It mentions four technologies: Near area time deterministic wired network (IEEE TSN, 802.1Qx), Mobile time deterministic network (5G TSC, TSN-TT), broad area deterministic wired network (IETF DetNet) and metro deterministic wired network (OIF FlexE, ITU-T SG15 G.mtn). This study also surveys all the patents related to low-latency technology, patents related to high-reliability technology, and patents related to mobile network technology, showing the extreme increase in the number of patents based on 3GPP specifications.

Time Synchronization is an important part of latency in low-latency applications. All gPTP systems exchange timing information between different network devices on the control plane. The load created in the control plane due to the time synchronization can have a great impact on low-latency applications. A solution to mitigate the load created in the control plane is to use a centralized time synchronization system where timing information messages are exchanged only between a central controller and individual network devices. This approach is similar to software-defined networking (SDN) [157,158] even though SDN technology in wired and fixed network is more advanced than the SDN-based mobile network developments [159].

Another review of URLLC as a key enabler of mission-critical services is presented in [20]. It overviews the state of the art of URLLC in the physical layer, link layer, and network layer summarizing the potential implementation methods of URLLC. In addition, this study also illustrates the challenges of mobile systems to support the integration of URLLC technology and identifies the need for meaningful models to fit practical scenarios. All these studies have surveyed the 3GPP Releases including the key components of 5G standards [160] and TSN standards [11, 161] separating them from each other.

5G-ACIA [18] aims at supporting 5G in the industrial domain and provides an insight overview of 5G in industrial applications, including the possible integration concepts and migration paths. There are a few white papers published by this organization that outline the critical requirements for interoperability and features of 5G. The integration of TSN and 5G is also addressed by this forum. The forum also explores how and why should the integration of TSN and 5G be applied in the industry. Their baseline is the 3GPP Release 16 for 5G specifications and IEEE standards for TSN specifications. We consider this paper since it provides not only an overview of the standards but also shows the TSN and 5G integration for various industrial automation use cases, i.e., controller-to-controller, controller-to-device, and device-to-compute communication.

Moreover, Parvez et al. [162] present several latency-critical applications which need to be supported by 5G. They also demonstrate the typical latency and data rate requirements for different mission-critical services, e.g, factory automation, robotics, virtual reality, and healthcare. Various solutions on RAN, Core Network, or caching solutions, are used to achieve low latency on a 5G system. 5G is also a promising solution for autonomous driving meeting the connectivity requirements of V2X communication for higher levels of autonomy [163].

The usage scenarios of 5G are also presented by Navarro-Ortiz et al. [164]. They present the most significant use cases expected for 5G including their scenarios and traffic models. Although this survey is focusing only on 5G, it performs useful analyses not only on the characteristics and requirements for 5G communications but also on 5G usage scenarios allowing 5G stakeholders and researchers to evaluate the performance of 5G solutions under the most critical requirements. Furthermore, 5G should be adapted to a wide range of scenarios such as indoor, urban, suburban, rural areas, etc, which will set new requirements for 5G channel modeling [165]. In addition, Ai et al. [160] have identified significant 5G-based key technologies for high-speed railways to develop innovative communication network architectures that ensure high-quality transmissions for both passengers and railway operations and control systems.

Recse et.al. [166] and Kaloxylos [167] advocate network slicing to be the key enabler to realize 5G in IoT. The use of the network slicing method can effectively guarantee the QoS requirements of different services by splitting the existing physical network to form multiple independent logical networks with customized services [168]. Even though the integration of TSN and 5G is not considered by the authors, the investigated technologies can provide a good foundation for converged wired and wireless architecture considering 5G. However, the research on the application of network slicing over TSN networks [82] is still in its infancy and the telecommunication organizations are still working on the standardization of such technology.

Scanzio, Wisniewski, and Gaj [169] perform an analysis of the state of the art in the area of heterogeneous industrial networks. This survey investigates both wired and wireless technologies considering technological aspects and performance targets, e.g., dependability. It also highlights the main challenges and communication requirements of industrial applications. 5G is also one of its targeted wireless technologies but the integration of wired and wireless technologies is still a challenge that they aim to consider as their future work.

Although 3GPP standards offer the possibility to converge TSN and 5G networks, a comprehensive overview of TSN-5G integration scenarios and a structured research map of the area is still missing. In this context, with this systematic literature review, we attempt to present all the current studies conducted in the scope of TSN-5G integration, while identifying the gaps in the existing research and highlighting further research opportunities for researchers and practitioners.

## 5.9 Conclusions

In this article, we presented the planning, execution, and results of a Systematic Literature Review (SLR) on the integration of TSN and 5G technologies. The

SLR provides a holistic overview and structured map of the state of the art research on TSN-5G integration. We identified 189 research studies in the initial phase of search and selection. After several refinements, we selected 82 of them as the primary studies that focus on the integration of TSN and 5G technologies. We extracted the required data from these primary studies by using a well-defined and thorough data extraction process. The extracted data was then analyzed and synthesized to answer the three research questions posed in this SLR.

The first research question was answered by analyzing the primary studies according to their technical contributions. We noticed that 74% of the studies follow the architecture proposed by the 3GPP working group, while still encountering difficulties on time synchronization, resource management, and flow management of the integrated system. Furthermore, the most commonly used time synchronization approach is the transparent clock approach that is proposed in the 3GPP specification. In addition, 72% (59 studies) of all the primary studies provide software design, while only 12 primary studies (15% of the total) present hardware design for the TSN and 5G integration. The majority of the primary studies (29 studies) use simulated networks for their empirical evaluation, while 19 studies use a real network to perform the evaluation of their TSN-5G suggested technique/approach.

The second research question was answered by classifying the primary studies according to well-defined classification criteria and showing the research trends in the area of TSN-5G integration. The results show that the interest of researchers in the area is continuously growing. The IEEE International Workshop on Factory Communication Systems (WFCS) and the IEEE International Conference on Emerging Technologies and Factory Automation (ETFA) have published the highest number of primary studies to date.

To answer the third research question, we used horizontal analysis to investigate the relationship between various sets of categories in the proposed classification. This analysis resulted in the identification of potential gaps in the research area and opportunities for future research. Among the others, it calls for the research community to develop prototypes of a tool that implements the scientific techniques for the integration of TSN and 5G technologies.

The results of this study are comprehensive enough for researchers and practitioners in identifying current research trends, potential gaps, and future research directions in the context of integrating TSN and 5G technologies. In the future, we plan to provide an approach for timing synchronization between TSN and 5G following the integration architecture suggested by the 3GPP working group. Another contribution to the research community would be to evaluate the timing approach using one of the well-known simulation frameworks, named OMNet++.

# Bibliography

[1] Martin Wollschlaeger, Thilo Sauter, and Juergen Jasperneite. The Future of Industrial Communication: Automation Networks in the Era of the Internet of Things and Industry 4.0. *IEEE Industrial Electronics Magazine*, 11(1):17–27, 2017.

[2] Adnan Aijaz and Mahesh Sooriyabandara. The Tactile Internet for Industries: A Review. *Proceedings of the IEEE*, 107(2):414–435, 2019.

[3] C. S. V. Gutiérrez, L. U. S. Juan, I. Z. Ugarte and V. M. Vilches. Time-sensitive networking for robotics. arXiv preprintarXiv:1804.07643, 2018.

[4] Adam Kostrzewa and Rolf Ernst. Achieving safety and performance with reconfiguration protocol for ethernet TSN in automotive systems. *Journal of Systems Architecture*, 118:102208, 2021.

[5] Frederick Prinz, Michael Schoeffler, Armin Lechler, and Alexander Verl. Dynamic real-time orchestration of I4.0 components based on time-sensitive networking, 06 2018. Procedia CIRP, vol. 72, pp. 910–915.

[6] Mohammad Ashjaei, Lucia Lo Bello, Masoud Daneshtalab, Gaetano Patti, Sergio Saponara, and Saad Mubeen. Time-Sensitive Networking in automotive embedded systems: State of the art and research opportunities. *Journal of Systems Architecture*, 117:102137, 2021.

[7] Ahmed Nasrallah, Akhilesh S. Thyagaturu, Ziyad Alharbi, Cuixiang Wang, Xing Shao, Martin Reisslein, and Hesham ElBakoury. Ultra-Low Latency (ULL) Networks: The IEEE TSN and IETF DetNet Standards and Related 5G ULL Research. *IEEE Communications Surveys & Tutorials*, 21(1):88–145, 2019.

[8] Libing Deng, Xiongren Xiao, Hong Liu, Renfa Li, and Guoqi Xie. A low-delay AVB flow scheduling method occupying the guard band in Time-Sensitive Networking. *Journal of Systems Architecture*, 129:102586, 2022.

[9] Mohammad Ashjaei, Mikael Sjödin, and Saad Mubeen. A novel frame preemption model in TSN networks. *Journal of Systems Architecture*, 116:102037, 2021.

[10] Saad Mubeen, Lucia Lo Bello, Masoud Daneshtalab, and Sergio Saponara. Guest Editorial: Special issue on parallel, distributed, and network-based processing in next-generation embedded systems. *Journal of Systems Architecture*, 117:102159, 2021.

[11] Lucia Lo Bello and Wilfried Steiner. A perspective on IEEE Time-sensitive Networking for Industrial Communication and Automation Systems. *Proceedings of the IEEE*, 107(6):1094–1120, 2019.

[12] Jeffrey G. Andrews, Stefano Buzzi, Wan Choi, Stephen V. Hanly, Angel Lozano, Anthony C. K. Soong, and Jianzhong Charlie Zhang. What will 5G be? *IEEE Journal on Selected Areas in Communications*, 32(6):1065–1082, 2014.

[13] Tengshun Yang, Shuling Wang, Bohua Zhan, Naijun Zhan, Jinghui Li, Shuangqing Xiang, Zhan Xiang, and Bifei Mao. Formal Analysis of 5G Authentication and Key Management for Applications (AKMA). *Journal of Systems Architecture*, 126:102478, 2022.

[14] Technical Specification Group Services and System Aspects; System architecture for the 5G system (5GS)(Release 16). Technical report, 3GPP TS 23.501, 10 2020.

[15] Security Architecture and Procedures for 5G System. Technical report, 3GPP TS 33.501, August 2020.

[16] Radio Resource Control (RRC) Protocol Specification. Technical report, 3GPP TS 38.331, 2020.

[17] Study on Enhancements for Cyber-Physical Control Applications in Vertical Domains. Technical report, 3GPP TR 22.832, 2019.

[18] 5G ACIA. 5G for Connected Industries and Automation, 2019. white paper.

[19] Mehdi Bennis, Mérouane Debbah, and H. Vincent Poor. Ultrareliable and Low-Latency Wireless Communication: Tail, Risk, and Scale. *Proceedings of the IEEE*, 106(10):1834–1853, 2018.

[20] Daquan Feng, Lifeng Lai, Jingjing Luo, Yi Zhong, Canjian Zheng, and Kai Ying. Ultra-reliable and low-latency communications: applications, opportunities and challenges. *Science China Information Sciences*, 64:1–12, 2021.

[21] Barbara Kitchenham and Pearl Brereton. A systematic review of systematic review process research in software engineering. *Information and Software Technology*, 55(12):2049–2075, Dec. 2013.

[22] Federico Ciccozzi, Lorenzo Addazi, Sara Abbaspour Asadollah, Björn Lisper, Abu Naser Masud, and Saad Mubeen. A Comprehensive Exploration of Languages for Parallel Computing. *ACM Comput. Surv.*, 55(2), jan 2022.

[23] Mostafa Khoshnevisan, Vinay Joseph, Piyush Gupta, Farhad Meshkati, Rajat Prakash, and Peerapol Tinnakornsrisuphap. 5G Industrial Networks With CoMP for URLLC and Time Sensitive Network Architecture. *IEEE Journal on Selected Areas in Communications*, 37(4):947–959, 2019.

[24] Dave Cavalcanti, Javier Perez-Ramirez, Mohammad Mamunur Rashid, Juan Fang, Mikhail Galeev, and Kevin B. Stanton. Extending Accurate Time Distribution and Timeliness Capabilities Over the Air to Enable Future Wireless Industrial Automation Systems. *Proceedings of the IEEE*, 107(6):1132–1152, 2019.

[25] Istvan Godor, Michele Luvisotto, Stefano Ruffini, Kun Wang, Dhruvin Patel, Joachim Sachs, Ognjen Dobrijevic, Daniel P. Venmani, Olivier Le Moult, Jose Costa-Requena, Aapo Poutanen, Chris Marshall, and Janos Farkas. A Look Inside 5G Standards to Support Time Synchronization for Smart Manufacturing. *IEEE Communications Standards Magazine*, 4(3):14–21, 2020.

[26] Kai Petersen, Robert Feldt, Shahid Mujtaba, and Michael Mattsson. Systematic Mapping Studies in Software Engineering. In *Proceedings of the 12th International Conference on Evaluation and Assessment in Software Engineering*, EASE'08, page 68–77, Swindon, GBR, 2008. BCS Learning & Development Ltd.

[27] Pearl Brereton, Barbara A. Kitchenham, David Budgen, Mark Turner, and Mohamed Khalil. Lessons from applying the systematic literature review process within the software engineering domain, 2007.

[28] Sandra Fabbri, Cleiton Silva, Elis Hernandes, Fábio Octaviano, André Di Thommazo, and Anderson Belgamo. Improvements in the StArt Tool to Better Support the Systematic Review Process. In *Proceedings of the*

*20th International Conference on Evaluation and Assessment in Software Engineering*, EASE '16, New York, NY, USA, 2016. Association for Computing Machinery.

[29] Vahid Garousi, Michael Felderer, and Mika V Mäntylä. Guidelines for including grey literature and conducting multivocal literature reviews in software engineering. Information and Software Technology 106 (2019), 101–121, 2019.

[30] Claes Wohlin. Guidelines for Snowballing in Systematic Literature Studies and a Replication in Software Engineering. In *Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering*, EASE '14, New York, NY, USA, 2014. Association for Computing Machinery.

[31] Kathy Charmaz and Linda Liska Belgrave. Grounded theory. The Blackwell encyclopedia of sociology, 2007.

[32] Mahin K. Atiq, Raheeb Muzaffar, Oscar Seijo, Inaki Val, and Hans-Peter Bernhard. When IEEE 802.11 and 5G Meet Time-Sensitive Networking. *IEEE Open Journal of the Industrial Electronics Society*, 3:14–36, 2022.

[33] IEEE Standard 802.1Qcc. IEEE Standard for Local and Metropolitan Area Networks–Bridges and Bridged Networks–Amendment 31: Stream Reservation Protocol (SRP) Enhancements and Performance Improvements, 10 2018.

[34] Martin Bjorklund. The YANG 1.1 data modeling language. RFC 7950, 2016.

[35] Rob Enns, Martin Björklund, Jürgen Schönwälder, and Andy Bierman. Network Configuration Protocol (NETCONF). *RFC 6241*, June 2011.

[36] Inés Álvarez, Andreu Servera, Julián Proenza, Mohammad Ashjaei, and Saad Mubeen. Implementing a First CNC for Scheduling and Configuring TSN Networks. In *2022 IEEE 27th International Conference on Emerging Technologies and Factory Automation (ETFA)*, pages 1–4, 2022.

[37] Andy Bierman, Martin Bjorklund, and Kent Watsen. RESTCONF protocol. RFC 8040, 2017.

[38] IEEE Std 802.1QTM. IEEE Standard for Local and Metropolitan Area Networks - Virtual Bridged Local Area Networks - Amendment 07: Multiple Registration Protocol. *Std 802.1ak-2007 (Amendment to IEEE Std 802.1QTM-2005)*, pages 1–115, 2007.

[39] Technical Specification Group Services and System Aspects; Study on enhancement of 5G System (5GS) for vertical and Local Area Network (LAN) services (Release 16). Technical report, 3GPP TR 23.734, 06 2019.

[40] IEEE Std 1588-2008. IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems, July 2008.

[41] Nikolaus Kerö, Andreas Puhm, Thomas Kernen, and Anton Mroczkowski. Performance and Reliability Aspects of Clock Synchronization Techniques for Industrial Automation. *Proceedings of the IEEE*, 107(6):1011–1026, 2019.

[42] Oliver Michel, Roberto Bifulco, Gábor Rétvári, and Stefan Schmid. The Programmable Data Plane: Abstractions, Architectures, Algorithms, and Applications. *ACM Comput. Surv.*, 54(4), may 2021.

[43] Nate Foster, Nick McKeown, Jennifer Rexford, Guru Parulkar, Larry Peterson, and Oguz Sunay. Using Deep Programmability to Put Network Owners in Control. *ACM SIGCOMM Computer Communication Review*, 50(4):82–88, oct 2020.

[44] Jean Pierre Thomesse. Fieldbuses and interoperability. *Control Engineering Practice*, 7(1):81–94, 1999.

[45] Rongkai Wang, Chaojie Gu, Shibo He, Zhiguo Shi, and Wenchao Meng. An interoperable and flat Industrial Internet of Things architecture for low latency data collection in manufacturing systems. *Journal of Systems Architecture*, 129:102631, 2022.

[46] Y. Katsube, K. Nagami, S. Matsuzawa, and H. Esaki. Internetworking based on cell switch router-architecture and protocol overview. *Proceedings of the IEEE*, 85(12):1998–2006, 1997.

[47] Zeinab Bakhshi and Guillermo Rodriguez-Navas. A Preliminary Roadmap for Dependability Research in Fog Computing. *ACM SIGBED Rev.*, 16(4):14–19, jan 2020.

[48] Martin Manderscheid, Gereon Weiss, and Rudi Knorr. Verification of network end-to-end latencies for adaptive ethernet-based cyber-physical systems. *Journal of Systems Architecture*, 88:23–32, 2018.

[49] Saad Mubeen, Elena Lisova, and Aneta Vulgarakis Feljan. Timing predictability and security in safety-critical industrial cyber-physical systems: A position paper. *Applied Sciences*, 10(9):3125, 2020.

[50] Yifan He, Dongrui She, Sander Stuijk, and Henk Corporaal. Efficient communication support in predictable heterogeneous MPSoC designs for streaming applications. *Journal of Systems Architecture*, 59(10, Part A):878–888, 2013. Smart Camera Architecture.

[51] Wenming Wang, Haiping Huang, Lingyan Xue, Qi Li, Reza Malekian, and Youzhi Zhang. Blockchain-assisted handover authentication for intelligent telehealth in multi-server edge computing environment. *Journal of Systems Architecture*, 115:102024, 2021.

[52] Ericsson Blog. This is the key to mobility robustness in 5G networks, 2020. [Online]. Available: https://www.ericsson.com/en/blog/2020/5/the-key-to-mobility-robustness-5g-networks.

[53] Maxime Louvel, Alain Plantec, and Jean-Philippe Babau. Resource management for multimedia applications, distributed in open and heterogeneous home networks. *Journal of Systems Architecture*, 59(3):121–134, 2013.

[54] Zohreh Sanaei, Saeid Abolfazli, Abdullah Gani, and Rajkumar Buyya. Heterogeneity in Mobile Cloud Computing: Taxonomy and Open Challenges. *IEEE Communications Surveys Tutorials*, 16(1):369–392, 2014.

[55] Venkatesh-Prasad Ranganath, Pradip Vallathol, and Pankaj Gupta. Compatibility Testing Using Patterns-Based Trace Comparison. In *Proceedings of the 29th ACM/IEEE International Conference on Automated Software Engineering*, ASE '14, page 469–478, New York, NY, USA, 2014. Association for Computing Machinery.

[56] Mohamed Amine Kafi, Jalel Ben Othman, and Nadjib Badache. A Survey on Reliability Protocols in Wireless Sensor Networks. *ACM Comput. Surv.*, 50(2), may 2017.

[57] Zhiwei Feng, Qingxu Deng, Mingyang Cai, and Jinghua Li. Efficient Reservation-based Fault-Tolerant Scheduling for IEEE 802.1Qbv Time-Sensitive Networking. *Journal of Systems Architecture*, 123:102381, 2022.

[58] Samuel T. Redwine and William E. Riddle. Software Technology Maturation. In *Proceedings of the 8th International Conference on Software Engineering*, ICSE '85, page 189–200, Washington, DC, USA, 1985. IEEE Computer Society Press.

[59] Eleftherios Kyriakakis, Maja Lund, Luca Pezzarossa, Jens Sparsø, and Martin Schoeberl. A time-predictable open-source TTEthernet end-system. *Journal of Systems Architecture*, 108:101744, 2020.

[60] Ana Larrañaga, M. Carmen Lucas-Estañ, Imanol Martinez, Iñaki Val, and Javier Gozalvez. Analysis of 5G-TSN Integration to Support Industry 4.0. In *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, volume 1, pages 1111–1114, Vienna, Austria, 2020. IEEE.

[61] David Ginthör, Johannes von Hoyningen-Huene, Rene Guillaume, and Hans Schotten. Analysis of Multi-user Scheduling in a TSN-enabled 5G System for Industrial Applications. In *2019 IEEE International Conference on Industrial Internet (ICII)*, pages 190–199, 2019.

[62] Dan Wang and Tao Sun. Leveraging 5G TSN in V2X Communication for Cloud Vehicle. In *2020 IEEE International Conference on Edge Computing (EDGE)*, pages 106–110, Beijing, China, 2020. IEEE.

[63] Rongxing Lu, Lan Zhang, Jianbing Ni, and Yuguang Fang. 5G Vehicle-to-Everything Services: Gearing Up for Security and Privacy. *Proceedings of the IEEE*, 108(2):373–389, 2020.

[64] Yuanzhi Ni, Lin Cai, Jianping He, Alexey Vinel, Yue Li, Hamed Mosavat-Jahromi, and Jianping Pan. Toward Reliable and Scalable Internet of Vehicles: Performance Analysis and Resource Management. *Proceedings of the IEEE*, 108(2):324–340, 2020.

[65] Roel Wieringa, Neil Maiden, Nancy Mead, and Colette Rolland. Requirements engineering paper classification and evaluation criteria: a proposal and a discussion. Requirements Engineering, vol. 11, no. 1, 2006.

[66] Saad Mubeen, Sara Abbaspour Asadollah, Alessandro Vittorio Papadopoulos, Mohammad Ashjaei, Hongyu Pei-Breivold, and Moris Behnam. Management of Service Level Agreements for Cloud Services in IoT: A Systematic Mapping Study. *IEEE Access*, 6:30184–30207, 2018.

[67] Daniela S. Cruzes and Tore Dyba. Recommended Steps for Thematic Synthesis in Software Engineering. In *2011 International Symposium on Empirical Software Engineering and Measurement*, pages 275–284, Banff, AB, Canada, 2011. IEEE.

[68] Daniel King and Adrian Farrel. A PCE-Based Framework for Future Internet Deterministic and Time-Sensitive Networks. In *2020 16th International Conference on Network and Service Management (CNSM)*, pages 1–7, Izmir, Turkey, 2020. IEEE.

[69] Jim Zou, Silviu Adrian Sasu, Mirko Lawin, Annika Dochhan, Jorg-Peter Elbers, and Michael Eiselt. Advanced optical access technologies for next-generation (5G) mobile networks [Invited]. *Journal of Optical Communications and Networking*, 12(10):D86–D98, 2020.

[70] Sa Math, Lejun Zhang, Seokhoon Kim, and Intae Ryoo. An Intelligent Real-Time Traffic Control Based on Mobile Edge Computing for Individual Private Environment. Security and Communication Networks, vol. 2020, Article ID 8881640, 11 pages, 2020.

[71] MiJeong Yang, SoonYong Lim, Sung-Min Oh, and Jaesheung Shin. An Uplink Transmission Scheme for TSN Service in 5G Industrial IoT. In *2020 International Conference on Information and Communication Technology Convergence (ICTC)*, pages 902–904, 2020.

[72] Jannis Ohms, Martin Böhm, and Diederich Wermser. Concept of a TSN to Real-Time Wireless Gateway in the Context of 5G URLLC. In *2020 8th International Conference on Wireless Networks and Mobile Communications (WINCOM)*, pages 1–6, Reims, France, 2020. IEEE.

[73] Yue Liu, Yiqing Zhou, Jinhong Yuan, and Ling Liu. Delay Aware Flow Scheduling for Time Sensitive Fronthaul Networks in Centralized Radio Access Network. *IEEE Transactions on Communications*, 68(5):2992–3009, 2020.

[74] David Ginthör, René Guillaume, Johannes von Hoyningen-Huene, Maximilian Schüngel, and Hans D. Schotten. End-to-end Optimized

Joint Scheduling of Converged Wireless and Wired Time-Sensitive Networks. In *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, volume 1, pages 222–229, 2020.

[75] Jim Zou, Silviu Adrian Sasu, John Messenger, and Jörg-Peter Elbers. Options for time-sensitive networking for 5G fronthaul. In *45th European Conference on Optical Communication (ECOC 2019)*, pages 1–3, Dublin, Ireland, 2019. IET.

[76] Christian Mannweiler, Borislava Gajic, Peter Rost, Rakash S. Ganesan, Christian Markwart, Ruediger Halfmann, Jens Gebert, and Andreas Wich. Reliable and Deterministic Mobile Communications for Industry 4.0: Key Challenges and Solutions for the Integration of the 3GPP 5G System with IEEE. In *Mobile Communication - Technologies and Applications; 24. ITG-Symposium*, pages 1–6, Osnabrueck, Germany, 2019. VDE.

[77] Renato B. Abreu, Guillermo Pocovi, Thomas H. Jacobsen, Marco Centenaro, Klaus I. Pedersen, and Troels E. Kolding. Scheduling Enhancements and Performance Evaluation of Downlink 5G Time-Sensitive Communications. *IEEE Access*, 8:128106–128115, 2020.

[78] Tobias Striffler, Nicola Michailow, and Michael Bahr. Time-Sensitive Networking in 5th Generation Cellular Networks - Current State and Open Topics. In *2nd IEEE 5G World Forum (5GWF)*, pages 547–552, Dresden, Germany, 2019. IEEE.

[79] Arne Neumann, Lukasz Wisniewski, Rakash SivaSiva Ganesan, Peter Rost, and Jürgen Jasperneite. Towards integration of Industrial Ethernet with 5G mobile networks. In *2018 14th IEEE International Workshop on Factory Communication Systems (WFCS)*, pages 1–4, Imperia, Italy, 2018. IEEE.

[80] Eda Genc and Luis Felipe Del Carpio. Wi-Fi QoS Enhancements for Downlink Operations in Industrial Automation Using TSN. In *2019 15th IEEE International Workshop on Factory Communication Systems (WFCS)*, pages 1–6, Sundsvall, Sweden, 2019. IEEE.

[81] Jonathan Prados-Garzon and Tarik Taleb. Asynchronous Time-Sensitive Networking for 5G Backhauling. *IEEE Network*, 35(2):144–151, 2021.

[82] Sushmit Bhattacharjee, Kostas Katsalis, Osama Arouk, Robert Schmidt, Tongtong Wang, Xueli An, Thomas Bauschert, and Navid Nikaein. Network Slicing for TSN-Based Transport Networks. *IEEE Access*, 9:62788–62809, 2021.

[83] János Farkas, Balázs Varga, György Miklós, and Joachim Sachs. 5G-TSN Integration Meets Networking Requirements for Industrial Automation. Ericsson Technology Review, vol. 96, no 7, 2019.

[84] Fei Song, Letian Li, Ilsun You, and Hongke Zhang. Enabling Heterogeneous Deterministic Networks with Smart Collaborative Theory. *IEEE Network*, 35(3):64–71, 2021.

[85] Jonathan Prados-Garzon, Tarik Taleb, and Miloud Bagaa. Optimization of Flow Allocation in Asynchronous Deterministic 5G Transport Networks by Leveraging Data Analytics, 2021.

[86] David Ginthör, René Guillaume, Maximilian Schüngel, and Hans D. Schotten. Robust End-to-End Schedules for Wireless Time-Sensitive Networks under Correlated Large-scale Fading. In *2021 17th IEEE International Conference on Factory Communication Systems (WFCS)*, pages 115–122, Linz, Austria, 2021. IEEE.

[87] Naotaka Shibata, Paikun Zhu, Kazuto Nishimura, Yuki Yoshida, Kazunori Hayashi, Masaki Hirota, Rintaro Harada, Kazuaki Honda, Shin Kaneko, Jun Terada, and Ken-Ichi Kitayama. Time Sensitive Networking for 5G NR Fronthauls and Massive IoT Traffic. *Journal of Lightwave Technology*, 39(16):5336–5343, 2021.

[88] Dave Cavalcanti. Wireless TSN – Definitions, Use Cases & Standards Roadmap, 2020. Avnu Alliance white paper.

[89] 5G ACIA. Integration of 5G with Time-Sensitive Networking for Industrial Communications, 2021. white paper.

[90] Gabriel Brown. Ultra-Reliable Low-Latency 5G for Industrial Automation. Qualcomm white paper, 2019.

[91] Razvan Petre. Testing Time-Sensitive Networking Over 5G: Time Synchronization (802.1AS), 2021. Accessed: 2021-11-20.

[92] Yajing Zhang, Qimin Xu, Mingyan Li, Cailian Chen, and Xinping Guan. QoS-Aware Mapping and Scheduling for Virtual Network Functions in Industrial 5G-TSN Network. In *2021 IEEE Global Communications Conference (GLOBECOM)*, pages 1–6, 2021.

[93] Hua Xu, Jincan Xin, Sen Xu, and Hua Zhang. RAN Enhancement to Support Propagation Delay Compensation of TSN. In *2021 IEEE 9th International Conference on Information, Communication and Networks (ICICN)*, pages 179–182, Xi'an, China, 2021. IEEE.

[94] Dhruvin Patel, John Diachina, Stefano Ruffini, Marilet De Andrade, Joachim Sachs, and Daniel Philip Venmani. Time error analysis of 5G time synchronization solutions for time aware industrial networks. In *2021 IEEE International Symposium on Precision Clock Synchronization for Measurement, Control, and Communication (ISPCS)*, pages 1–6, NA, FL, USA, 2021. IEEE.

[95] Ogechi Akudo Nwogu, Gladyz Diaz, and Marwen Abdennebi. Differential Traffic QoS Scheduling for 5G/6G Fronthaul Networks. In *2021 31st International Telecommunication Networks and Applications Conference (ITNAC)*, pages 113–120, Sydney, 2021. IEEE.

[96] Zhengqiang Liu, Haiyang Wang, Haipeng Sun, Junhao Su, Bo Zhang, Minggang Liu, and Ruijie Zhu. Software Defined Network based 5G and Time- Sensitive Network Fusion For Power services with Ultra-low Latency Requirements. In *2021 International Conference on Wireless Communications and Smart Grid (ICWCSG)*, pages 381–385, Hangzhou, China, 2021. IEEE.

[97] Zichao Chai, Wei Liu, Mao Li, and Jing Lei. Cross Domain Clock Synchronization Based on Data Packet Relay in 5G-TSN Integrated Network. In *2021 IEEE 4th International Conference on Electronics and Communication Engineering (ICECE)*, pages 141–145, Xi'an, China, 2021. IEEE.

[98] Chinchilla-Romero Lorena, Jonathan Prados-Garzon, Pablo Ameigeiras, Pablo Muñoz, and Juan M. Lopez-Soler. 5G Infrastructure Network Slicing: E2E Mean Delay Model and Effectiveness Assessment to Reduce Downtimes in Industry 4.0. Sensors 22, no. 1: 229, 2022.

[99] Yajing Zhang, Qimin Xu, Cailian Chen, and Mingyan Li. Wireless/wired integrated transmission for industrial cyber-physical systems: risk-sensitive co-design of 5G and TSN protocols. Science China Information Sciences, 65, 2022.

[100] Wan Lei, Anthony C. K Soong, Liu Jianghua, Wu Yong, Brian Classon, Weimin Xiao, David Mazzarese, Zhao Yang, and Tony Saboorian. 5G Industrial IoT. In *Wireless Networks*, pages 515–532, 2021.

[101] Zenepe Satka, David Pantzar, Alexander Magnusson, Mohammad Ashjaei, Hossein Fotouhi, Mikael Sjödin, Masoud Daneshtalab, and Saad Mubeen. Developing a Translation Technique for Converged TSN-5G Communication. In *2022 IEEE 18th International Conference on Factory Communication Systems (WFCS)*, pages 1–8, 2022.

[102] Pierre Kielhs, Junaid Ansari, Mohammad Hossein Jafari, Paul Becker, Joachim Sachs, Niels König, Amon Göppert, and Robert H. Schmitt. Prototype of 5G Integrated with TSN for Edge-Controlled Mobile Robotics. *International Journal of Electronics and Telecommunications*, 11(11), 2022.

[103] Francisco Luque-Schempp, Laura Panizo, María-del-Mar Gallardo, Pedro Merino, and Javier Rivas. Toward Zero Touch Configuration of 5G Non-Public Networks for Time Sensitive Networking. *IEEE Network*, 36(2):50–56, 2022.

[104] Kota Nikhileswar, Krishnanand Prabhu, and Dave Cavalcanti. Traffic Steering in Edge Compute Devices using eXpress Data Path for 5G and TSN Integration. In *2022 IEEE 18th International Conference on Factory Communication Systems (WFCS)*, pages 1–6. IEEE, 2022.

[105] Jeff Shepard. When Will 5G Enter Industrial TSN?, 2022. Accessed: 2022-07-13.

[106] Peter M. Rost and Troels Kolding. Performance of Integrated 3GPP 5G and IEEE TSN Networks. *IEEE Communications Standards Magazine*, 6(2):51–56, 2022.

[107] Xiaoming Li, Yingying Chi, Xiaoguang Jia, and Yong Xie. Research on Integration of 5G and TSN, 2022. Advances in Transdisciplinary Engineering.

[108] Guoyu Peng, Shuo Wang, Yudong Huang, Tao Huang, and Yunjie Liu. Enabling deterministic tasks with multi-access edge computing in 5g networks. *IEEE Communications Magazine*, 60(8):36–42, 2022.

[109] Jingwei Yang and Guanding Yu. Traffic scheduling for 5g-tsn integrated systems. In *2022 International Symposium on Wireless Communication Systems (ISWCS)*, pages 1–6, 2022.

[110] Yilong Chen, Xianqiong Yao, Zhong Gan, Zhaoyang You, Peng Wu, and Wei Wang. Power service mapping scheduling method based on fusion of 5g and time-sensitive network. In *2022 IEEE 6th Advanced Information Technology, Electronic and Automation Control Conference (IAEAC )*, pages 1309–1314, 2022.

[111] Kota Nikhileswar, Krishnanand Prabhu, Dave Cavalcanti, and Alon Regev. Time-sensitive networking over 5g for industrial control systems. In *2022 IEEE 27th International Conference on Emerging Technologies and Factory Automation (ETFA)*, pages 1–8, 2022.

[112] Hua Zhang, Na Lu, Weiliang Xie, and Peng Li. Analysis of the Use Cases and Technical Enhancements of TSN. In *2021 2nd Information Communication Technologies Conference (ICTC)*, pages 288–291, Nanjing, China, 2021. IEEE.

[113] Lukas Martenvormfelde, Arne Neumann, Lukasz Wisniewski, and Jürgen Jasperneite. A Simulation Model for Integrating 5G into Time Sensitive Networking as a Transparent Bridge. In *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation*, volume 1, pages 1103–1106, 2020.

[114] Zenepe Satka, Mohammad Ashjaei, Hossein Fotouhi, Masoud Daneshtalab, Mikael Sjödin, and Saad Mubeen. QoS-MAN: A Novel QoS Mapping Algorithm for TSN-5G Flows. In *2022 IEEE 28th International Conference on Embedded and Real-Time Computing Systems and Applications (RTCSA)*, pages 220–227, 2022.

[115] Maximilian Schüngel, Steven Dietrich, David Ginthör, Shun-Ping Chen, and Michael Kuhn. Analysis of time synchronization for converged wired and wireless networks. In *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, volume 1, pages 198–205, Vienna, Austria, 2020. IEEE.

[116] Michael Gundall, Christopher Huber, Peter Rost, Rüdiger Halfmann, and Hans D. Schotten. Integration of 5G with TSN as Prerequisite for a Highly Flexible Future Industrial Automation: Time Synchronization based on IEEE 802.1AS. In *IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society*, pages 3823–3830, Singapore, 2020. IEEE.

[117] Maximilian Schüngel, Steven Dietrich, David Ginthör, Shun-Ping Chen, and Michael Kuhn. Single Message Distribution of Timing In-

formation for Time Synchronization in Converged Wired and Wireless Networks. In *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation*, volume 1, pages 286–293, 2020.

[118] Sushmit Bhattacharjee, Robert Schmidt, Kostas Katsalis, Chia-Yu Chang, Thomas Bauschert, and Navid Nikaein. Time-Sensitive Networking for 5G Fronthaul Networks. In *ICC 2020 - 2020 IEEE International Conference on Communications (ICC)*, pages 1–7, Dublin, 2020. IEEE.

[119] Jayanta Kumar Ray, Pallabi Biswas, Rabindranath Bera, Sanjib Sil, and Quazi Mohmmad Alfred. TSN enabled 5G Non Public Network for Smart Systems. In *2020 5th International Conference on Computing, Communication and Security (ICCCS)*, pages 1–6, Patna, India, 2020. IEEE.

[120] Fatemeh Hamidi-Sepehr, Masoud Sajadieh, Sergey Panteleev, Toufiqul Islam, Ingolf Karls, Debdeep Chatterjee, and Junaid Ansari. 5G URLLC: Evolution of High-Performance Wireless Networking for Industrial Automation. *IEEE Communications Standards Magazine*, 5(2):132–140, 2021.

[121] Naotaka Shibata, Paikun Zhu, Kazuto Nishimura, Yuki Yoshida, Kazunori Hayashi, Masaki Hirota, Rintaro Harada, Kazuaki Honda, Shin Kaneko, Jun Terada, and Ken-ichi Kitayama. First Demonstration of Autonomous TSN-based Beyond-Best-Effort Networking for 5G NR Fronthauls and 1,000+ Massive IoT Traffic. In *2020 European Conference on Optical Communications (ECOC)*, pages 1–4, Brussels, Belgium, 2020. IEEE.

[122] Aamir Mahmood, Muhammad Ikram Ashraf, Mikael Gidlund, Johan Torsner, and Joachim Sachs. Time Synchronization in 5G Wireless Edge: Requirements and Solutions for Critical-MTC. *IEEE Communications Magazine*, 57(12):45–51, 2019.

[123] Maximilian Schüngel, Steven Dietrich, Ludwig Leurs, David Ginthör, Shun-Ping Chen, and Michael Kuhn. Advanced Grandmaster Selection Method for Converged Wired and Wireless Networks. In *2021 22nd IEEE International Conference on Industrial Technology (ICIT)*, volume 1, pages 1007–1014, Valencia, Spain, 2021. IEEE.

[124] Oscar Seijo, Inaki Val, Michele Luvisotto, and Zhibo Pang. Clock Synchronization for Wireless Time-Sensitive Networking: A March From Microsecond to Nanosecond, 2021.

[125] Haochuan Shi, Adnan Aijaz, and Nan Jiang. Evaluating the Performance of Over-the-Air Time Synchronization for 5G and TSN Integration. In *2021 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom)*, pages 1–6, Bucharest, Romania, 2021. IEEE.

[126] Maximilian Schüngel, Steven Dietrich, David Ginthör, Shun-Ping Chen, and Michael Kuhn. Heterogeneous Synchronization in Converged Wired and Wireless Time-Sensitive Networks. In *2021 17th IEEE International Conference on Factory Communication Systems (WFCS)*, pages 67–74, Linz, Austria, 2021. IEEE.

[127] Tobias Striffler and Hans D. Schotten. The 5G Transparent Clock: Synchronization Errors in Integrated 5G-TSN Industrial Networks. In *2021 IEEE 19th International Conference on Industrial Informatics (INDIN)*, pages 1–6, Palma de Mallorca, Spain, 2021. IEEE.

[128] Jiajia Song, Makoto Kubomi, Jeffrey Zhao, and Daisuke Takita. Time synchronization performance analysis considering the frequency offset inside 5G-TSN network. In *2021 17th International Symposium on Wireless Communication Systems (ISWCS)*, pages 1–6, Berlin, Germany, 2021. IEEE.

[129] 5G Smart Project. 5G E2E Technology To Support Verticals URLLC Requirements, 2019. white paper.

[130] Comcores. Delivering timing accuracy in 5G networks. white paper, 2020. Accessed: 2021-11-20.

[131] Christine Boles. Shaping the future of the industrial IoT with TSN-over-5G, 2020. Accessed: 2021-11-20.

[132] Hongxing Li, Dengkui Li, Xiaodong Zhang, Guochu Shou, Yihong Hu, and Yaqiong Liu. A Security Management Architecture for Time Synchronization Towards High Precision Networks. *IEEE Access*, 9:117542–117553, 2021.

[133] Xiaohan Wei, Xingzhong Xiong, Zhongqiang Luo, Jianwu Wang, and Kaixing Cheng. An enhanced IEEE1588 clock synchronization for link

delays based on a system-on-chip platform. *International Journal of Electronics and Telecommunications*, pages 289–294, 2021.

[134] Junaid Ansari, Tien-sung Hsiao, Mohammad Hossein Jafari, Balázs Varga, János Farkas, István Moldován, Amon Göppert, and Robert H. Schmitt. 5g enabled flexible lineless assembly systems with edge cloud controlled mobile robots. In *2022 IEEE 33rd Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, pages 1419–1424, 2022.

[135] Ritu Sethi, Akshay Kadam, Krishnanand Prabhu, and Nikhileswar Kota. Security considerations to enable time-sensitive networking over 5g. *IEEE Open Journal of Vehicular Technology*, 3:399–407, 2022.

[136] Andrea Garbugli, Lorenzo Rosa, Luca Foschini, Antonio Corradi, and Paolo Bellavista. A framework for tsn-enabled virtual environments for ultra-low latency 5g scenarios. In *ICC 2022 - IEEE International Conference on Communications*, pages 5023–5028, 2022.

[137] Minh-Thuyen Thi, Sosthène Guédon, Siwar Ben Hadj Said, Michael Boc, David Miras, Jean-Baptiste Dore, Marc Laugeois, Xavier Popon, and Benoit Miscopein. Ieee 802.1 tsn time synchronization over wi-fi and 5g mobile networks. In *2022 IEEE 96th Vehicular Technology Conference (VTC2022-Fall)*, pages 1–7, 2022.

[138] Yongjing Li, Dan Wang, Tao Sun, Xiaodong Duan, and Lu Lu. Solutions for Variant Manufacturing Factory Scenarios Based on 5G Edge Features. In *2020 IEEE International Conference on Edge Computing (EDGE)*, pages 54–58, Beijing, China, 2020. IEEE.

[139] Lalit Chettr and Rabindranath Bera. Industry 4.0: Communication Technologies, Challenges and Research Perspective Towards 5G Systems. In *Advances in Communication, Devices and Networking*, volume 662, pages 67–77, Singapore, 2020. Springer, Singapore.

[140] Jens Gebert and Andreas Wich. Alternating Transmission of Packets in Dual Connectivity for Periodic Deterministic Communication Utilising Survival Time. In *2020 European Conference on Networks and Communications (EuCNC)*, pages 160–164, Dubrovnik, Croatia, 2020. IEEE.

[141] Jessy Cavazos. 5G Is Enabling Private Networks For Industry 4.0, 2022. Accessed: 2022-07-13.

[142] Peng Ding, Dan Liu, Yun Shen, Huibin Duan, and Qiuhong Zheng. Edge-to-cloud intelligent vehicle-infrastructure based on 5g time-sensitive network integration. In *2022 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*, pages 1–5, 2022.

[143] Jiayu Huang, Lei Feng, Fanqin Zhou, Huiyong Liu, Peng Yu, and Kunyi Xie. 5g urllc local deployment architecture for industrial tsn services. In *2022 International Wireless Communications and Mobile Computing (IWCMC)*, pages 7–11, 2022.

[144] Jacob Cohen. A coefficient of agreement for nominal scales, April 1960. Edu. Psychol. Meas., vol. 20, no. 1.

[145] J. L. Fleiss. Measuring nominal scale agreement among many raters, 1971. Psychol. Bull., vol. 76, no. 5, pp. 378–382.

[146] M. L. McHugh. Interrater reliability: The kappa statistic, 2012. Biochemia medica, vol. 22, no. 3, pp. 276–282.

[147] Claes Wohlin, Per Runeson, Martin Höst, Magnus C Ohlsson, Björn Regnell, and Anders Wesslén. *Experimentation in Software Engineering*. Springer, Germany, 2012.

[148] Amitabha Ghosh, Andreas Maeder, Matthew Baker, and Devaki Chandramouli. 5G Evolution: A View on 5G Cellular Technology Beyond 3GPP Release 15. *IEEE Access*, 7:127639–127651, 2019.

[149] Anja Jerichow, Betsy Covell, Devaki Chandramouli, Ali Rezaki, Atte Lansisalmi, and Juergen Merkel. 3GPP Non-Public Network Security, 2020. Vol 8 Iss 1.

[150] Cosmas Ifeanyi Nwakanma, Alifia Putri Anantha, Fabliha Bushra Islam, Jae-Min Lee, and Dong-Seong Kim. 3GPP Release-16 for Industrial Internet of Things and Mission Critical Communications. In *2020 International Conference on Information and Communication Technology Convergence (ICTC)*, pages 403–406, Jeju, Korea (South), 2020. IEEE.

[151] Sunmi Jun, Yoohwa Kang, Jaeho Kim, and Changki Kim. Ultra-low-latency services in 5G systems: A perspective from 3GPP standards, 2020. ETRI J., 42, 721–733.

[152] Silviu S. Craciunas and Ramon Serna Oliver. An Overview of Scheduling Mechanisms for Time-sensitive Networks. In *Proceedings of the Real-Time Summer School LÉcole dÉté Temps Réel*, 2017.

[153] Soheil Samii and Helge Zinner. Level 5 by Layer 2: Time-Sensitive Networking for Autonomous Vehicles. *IEEE Communications Standards Magazine*, 2(2):62–68, 2018.

[154] Libing Deng, Guoqi Xie, Hong Liu, Yunbo Han, Renfa Li, and Keqin Li. A Survey of Real-Time Ethernet Modeling and Design Methodologies: From AVB to TSN. *ACM Comput. Surv.*, 55(2), jan 2022.

[155] Bob Briscoe, Anna Brunstrom, Andreas Petlund, David Hayes, David Ros, Ing-Jyh Tsang, Stein Gjessing, Gorry Fairhurst, Carsten Griwodz, and Michael Welzl. Reducing Internet Latency: A Survey of Techniques and Their Merits. *IEEE Communications Surveys Tutorials*, 18(3):2149–2196, 2016.

[156] J. W. Won, J. M. Ahn. 3GPP URLLC patent analysis. ICT Express, September 2020. https://doi.org/10.1016/j.icte.2020.09.001.

[157] Bander Alzahrani and Nikos Fotiou. Enhancing Internet of Things Security using Software-Defined Networking. *Journal of Systems Architecture*, 110:101779, 2020.

[158] Md. Mahmudul Islam, Muhammad Toaha Raza Khan, Malik Muhammad Saad, and Dongkyun Kim. Software-defined vehicular network (SDVN): A survey on architecture and routing. *Journal of Systems Architecture*, 114:101961, 2021.

[159] Zainab Zaidi, Vasilis Friderikos, Zarrar Yousaf, Simon Fletcher, Mischa Dohler, and Hamid Aghvami. Will SDN Be Part of 5G? *IEEE Communications Surveys Tutorials*, 20(4):3220–3258, 2018.

[160] Bo Ai, Andreas F. Molisch, Markus Rupp, and Zhang-Dui Zhong. 5G Key Technologies for Smart Railways. *Proceedings of the IEEE*, 108(6):856–893, 2020.

[161] Mubarak Adetunji Ojewale, Patrick Meumeu Yomsi, and Borislav Nikolić. Worst-case traversal time analysis of TSN with multi-level preemption. *Journal of Systems Architecture*, 116:102079, 2021.

[162] Imtiaz Parvez, Ali Rahmati, Ismail Guvenc, Arif I. Sarwat, and Huaiyu Dai. A Survey on Low Latency Towards 5G: RAN, Core Network and Caching Solutions. *IEEE Communications Surveys Tutorials*, 20(4):3098–3130, 2018.

[163] Manzoor Ahmed Khan, Hesham El Sayed, Sumbal Malik, Talha Zia, Jalal Khan, Najla Alkaabi, and Henry Ignatious. Level-5 Autonomous Driving—Are We There Yet? A Review of Research Literature. *ACM Comput. Surv.*, 55(2), jan 2022.

[164] Jorge Navarro-Ortiz, Pablo Romero-Diaz, Sandra Sendra, Pablo Ameigeiras, Juan J. Ramos-Munoz, and Juan M. Lopez-Soler. A Survey on 5G Usage Scenarios and Traffic Models. *IEEE Communications Surveys Tutorials*, 22(2):905–929, 2020.

[165] Hao Jiang and Guan Gui. *Channel Modeling in 5G Wireless Communication Systems*. Springer Publishing Company, Incorporated, Springer, 1st edition, 2019.

[166] Akos Recse, Robert Szabo, and Balazs Nemeth. *Elastic Resource Management and Network Slicing for IoT over Edge Clouds*. 2020.

[167] Alexandros Kaloxylos. Network Slicing for 5G Networks: A Survey and an Analysis of Future Trends. In *Proceedings of the 21st Pan-Hellenic Conference on Informatics*, PCI 2017, New York, NY, USA, 2017. Association for Computing Machinery.

[168] Gregory Blanc, Nizar Kheir, Dhouha Ayed, Vincent Lefebvre, Edgardo Montes de Oca, and Pascal Bisson. Towards a 5G Security Architecture: Articulating Software-Defined Security and Security as a Service. In *ACM Proceedings of the 13th International Conference on Availability, Reliability and Security*, ARES 2018, New York, NY, USA, 2018. Association for Computing Machinery.

[169] Stefano Scanzio, Lukasz Wisniewski, and Piotr Gaj. Heterogeneous and dependable networks in industry – A survey, 2021. Computers in Industry, 125, https://doi.org/10.1016/j.compind.2020.103388.

# Chapter 6

# Paper B: Developing a Translation Technique for Converged TSN-5G Communication

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

## 6.1 Introduction

Many industrial applications require convergence of wired and wireless networks with deterministic end-to-end latency [1,2]. Such a converged network can lead to a more transparent network communication, allowing parts of the Operational Technology (OT) and Information Technology (IT) sectors in a smart factory to have a homogeneous layout. In today's industrial networks, the OT domain is made up of 90% vendor-locked wired technologies with limited throughput [3]. With parts of the smart factory network being wireless, one near-term benefit would be the significant reduction in utilization of cables, which in turn would reduce production costs [1].

Consider the automotive domain where an autonomous mine or a quarry consists of several autonomous vehicles and their control center. These vehicles can be equipped with numerous high data-rate sensors that can generate hundreds of megabytes of data per second (e.g., radars, Lidars and video cameras). Furthermore, the large amount of data acquired from these sensors needs to be communicated with predictable and low latencies between the computing units within the vehicles as well as among the vehicles and their control centre. Similar applications can be found in the other domains. In these applications, the IEEE TSN standards[1], based on the switched Ethernet, stand out as a promising solution to provide high-bandwidth and low-latency onboard communication [4]. Similarly, 5G offers a promising solution to support low-latency communication among these vehicles as well as between each vehicle and its remote control center. A converged TSN and 5G network can meet the high-bandwidth and low-latency end-to-end communication requirements, lower the number of vendor-specific requirements, and introduce a greater level of flexibility in the network communication.

In order to support such a converged end-to-end network communication, we propose a technique to translate the traffic between TSN and 5G communication technologies. This translation acts as a gateway between the two technologies by taking the necessary properties from TSN and mapping them to the 5G Quality of Service (QoS) according to the 3GPP specifications [5] and vice versa. We present a proof-of-concept implementation of the proposed technique in a commonly used TSN network simulator NeSTiNG [6] that is based on OMNeT++. Furthermore, we evaluate the translation technique using an automotive industrial use case. We show that the technique can assist network designers to evaluate various holistic TSN-5G network configurations.

---

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

## 6.2 Background and Related Work

### 6.2.1 Time Sensitive Networking (TSN)

TSN is a set of standards based on switched Ethernet. It supports high-bandwidth and low-latency communication, gaining attention in time-critical industrial applications such as in the industrial automation [7] and automotive domains [4, 8]. To improve the 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.

The TSN bridges (switches) are time-synchronized using IEEE 802.1AS. There are eight different classes of priority for TSN frames. This priority is defined using the Priority Code Point (PCP) field added in 802.1Q-2018 VLAN. We use two scheduling techniques available in TSN: the AVB Credit-Based Shaper (CBS) standardized in 802.1Qav, and the Time-Aware Shaper (TAS) based on Time Division Multiple Access (TDMA), where critical and non-critical traffic are assigned different time slots. For each priority queue, there is a gate that controls the egress data flow. A Gate Control List (GCL) contains the gate states of each queue at each time slot. A model of the functions of TSN bridge is presented in Fig. 6.1. It contains traffic class queues, a transmission scheduling algorithm, and a gate control list. The queues are numbered from 0 to 7 and Best Effort (BE), with 7 being the highest priority queue.

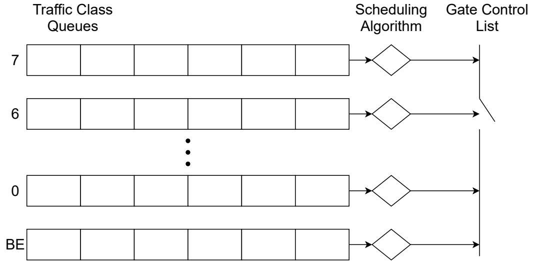


**Figure 6.1:** A TSN bridge model with the traffic class queues, transmission scheduling algorithm and gate control list.

To be able to guarantee that the schedule is followed and no frame/message[2] exceeds its time slot, a guard band of the size of the next message, or maximum message size is included at the end of each scheduling cycle. Such a schedule can be obtained by using existing methods, e.g., [9]. On the other hand, CBS is based on a token bucket shaper. When messages are pending in

---

[2] We consider the messages that fit only one frame.

a queue the credit increases, while it decreases when the messages are transmitted. This helps in preventing starvation of low-priority traffic and allows predictable traffic transmission.

### 6.2.2 5G and URLLC

The fifth generation of wireless communications (5G) [10, 11] provides significant improvements to the long term evolution (LTE) technology. It is designed to achieve low latency and reliability, providing the built-in flexibility required by Industry 4.0. 5G includes three generic services: enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and URLLC, [12–14]. 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 Release 17. With URLLC features, the new 5G Radio Access Network (RAN) [15] can achieve ultra-low latency down to 1 ms and reliability up to 99.9999%. Within the core network, latency is typically below 1 ms [16]. The desired QoS requirements for URLLC depend on the applications as shown in Table 6.1.

### 6.2.3 5G as a Logical TSN Bridge

Integration of 5G into TSN is based on either having 5G with the capabilities of TSN or integrating 5G as a logical TSN bridge. In the first approach, 5G is seen as a cable link between the devices [5], while in the second approach, 5G is seen as a black-box TSN bridge. 5G as a logical TSN bridge approach is the most focused in the existing works [17, 18].

3GPP provides two design approaches for using 5G as a logical TSN bridge [19]. The first approach has the translator located within the User Plane Function (UPF). In this architecture, the UPF and TSN Translator (TT) are seen as one component, where the translation of parameters between TSN and 5G takes place within the UPF. In the second design approach, the TSN translators are established on the device-side (DS-TT) and the network-side (NW-TT) of the logical TSN bridge. From the user plane's (UP) perspective, the logical TSN Bridge is a virtual tunnel between the UE and the TSN Network. The DS-TT translates the necessary parameters of TSN to 5G QoS to establish the message's priority on the device-side. This is transmitted from the RAN to the network-side, which holds the TSN network. The NW-TT handles the translation from the 5G QoS to TSN QoS so that the frame maintains correct priority within the integrated network [5]. The introduction of the TSN translators at the device-side and network-side makes it possible to reuse many of the existing interfaces defined for the 5G systems. Integrating the translator at the UPF would require the 5G system functionalities to communicate via the Session Management Function (SMF) [19].

**Table 6.1:** Expected QoS requirements for URLLC [14, 20].

| 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 |

### 6.2.4 Related Works

There are very few works that focus on the integration of TSN and 5G communication. Most of the works consider challenges related to clock synchronization, while bridging between the two domains has received little attention. For example, Schüngel *et al.* [21] consider the integration of 5G as a TSN virtual bridge. They provide a single message mechanism for signalling timing information through the virtual TSN bridge leveraging the underlying synchronization of the 5G system. For evaluation, they use a discrete event simulator OMNEST [22] (a commercial version of OMNeT++).

There are very few works that address simulation of integrated TSN and 5G networks. Ginthör et al. [23] present a system-level simulator considering the impact and requirements of TSN end-to-end systems. They use OMNeT++ with NeSTiNg model to simulate a TSN-5G network by following the specifications of 3GPP Release 15. By converting a 4G architecture, they added characteristics such as Ethernet PDU sessions and packet filter sets supporting MAC addressing, mini-slots, high-reliability modulation, and 5G quality-of-service indicators, which are required for 5G communication. Their simulation setup consisted of multiple user equipment that are connected to one base station with a strict prioritization scheme. In comparison, we do not convert 4G to 5G. Furthermore, we consider 3GPP Release 16, which provides more details for time-sensitive communications.

Martenvormfelde et al. [24] present a simulation model for integrating 5G into TSN as a transparent bridge. They utilize OMNET++, NeSTiNg and a 5G user plane model. Their bridge model is limited to the user plane, derived from the 3GPP 5G architectural model, and is capable of uplink and downlink traffic. Certain characteristics of the New Radio frame structure and sub-carrier spacing of their model affected the end-to-end delay, even in smaller networks. This paper claims that to provide QoS guarantees in large networks, the model should handle 5G quality-of-service indicators, enabling priorities and queues similar to the TSN IEEE 802.1Q. To do so, we map the TSN QoS to the 5G QoS.

To the best of our knowledge, the research on TSN-5G integration is still in its infancy, mainly focusing on timing information and not on the traffic mapping with QoS management. We present a technique to translate the traffic between TSN and 5G domains considering the properties in the 3GPP-R16 specifications. Furthermore, we provide a proof-of-concept implementation of the technique in a well-known simulator for TSN.

## 6.3 TSN-5G Translator Design

In this section, we present the design of the TSN-5G translator. First we describe the focused QoS parameters. Then we present the translator's design and its proof-of-concept implementation in OMNET++ simulator.

### 6.3.1 5G QoS Indicators (5QIs)

The 5G QoS indicators is a list of parameters representing commonly used values for certain types of traffic [5]. Some of the 5QIs focused in this work are as follows.

- *Resource Type:* In 5G, the resource type parameter indicates how the Packet Delay Budget, Packet Error Rate, and Maximum Data Burst Volume should be handled. The resource can be of type Guaranteed Bit Rate (GBR), Non-GBR, or Delay-Critical GBR.

- *Default Priority Level:* The priority level indicates the scheduling priority of a QoS message. The standardized 5QIs assign their own default priority values, indicating the highest priority message with the lowest value of the default priority level parameter.

- *Packet Delay Budget (PDB):* It defines an upper bound on how long a packet can be delayed between the User Equipment (UE) and the User Plane Function (UPF). The UPF represents the communication scheme between the base station (gNB) and the NW-TT.

- *Packet Error Rate (PER):* It defines the level of reliability by providing an upper bound on the number of messages that can be processed and sent by the 5G node, but never arrive at their intended destination.
- *Default Maximum Data Burst Volume (MDBV):* It indicates the amount of data that can be sent within a PDB.
- *Default Averaging Window:* Indicates the calculation time of Guaranteed Flow Bit Rate (GFBR) and Maximum Flow Bit Rate (MFBR). 5G is expected to provide a guaranteed bit rate that is represented by GFBR. The MFBR defines the maximum value of an actual bit rate.

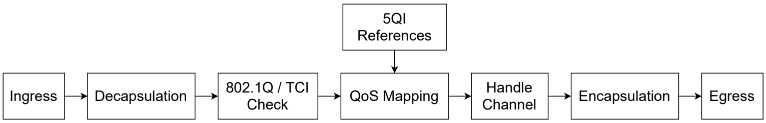
A representation of 5QIs for Delay-Critical GBR resources that are recommended for integration with TSN is shown in Table. 6.2. The listed parameters are part of a more extensive list of statically assigned parameters specified in the 3GPP specifications [5]. These parameters can also be set dynamically for highly specified scenarios.

**Table 6.2:** 5QIs for standardized Delay-Critical GBR.

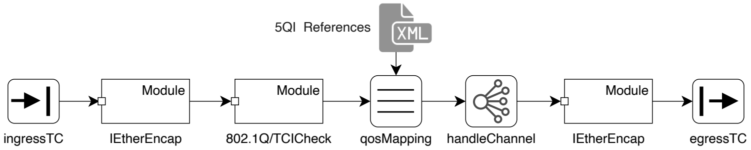
| **5QI Value** | **Resource Type** | **Default Priority Level** | **PDB** | **PER** | **MDBV (bytes)** | **Default Averaging Window** |
|---|---|---|---|---|---|---|
| 82 | Delay Critical GBR | 19 | 10 ms | $10^{-4}$ | 255 | 2000 ms |
| 83 | Delay Critical GBR | 22 | 10 ms | $10^{-4}$ | 1354 | 2000 ms |
| 84 | Delay Critical GBR | 24 | 30 ms | $10^{-6}$ | 1354 | 2000 ms |
| 85 | Delay Critical GBR | 21 | 5 ms | $10^{-5}$ | 255 | 2000 ms |

We focus on the user plane and translation of incoming frames so that they can be transmitted between TSN and 5G networks. Mapping of QoS messages to maintain the priority of the message in both networks is done by checking the Priority Code Point (PCP) value in the TSN frame. This value indicates how the 5G system should change its 5QI, which are parameters predetermined as discussed in Table 6.2. Once a frame arrives at the translator, it is first determined what type of translation has to be done by checking the data's interface. There are two possible types of translation in this scenario: *i)* TSN to 5G translation, and *ii)* 5G to TSN translation. As a proof of concept, each component of the translator is presented as a model or sub-model in OMNeT++ simulator.

***1) TSN to 5G - Translation Flow:*** To guarantee that the QoS in both 5G and TSN message is upheld, there are specific attributes of TSN that need to



(a) TSN to 5G Translation Flow.



(b) A proof-of-concept implementation of TSN to 5G Translation Flow in OMNeT++.

**Figure 6.2:** The translation flow from TSN to 5G networks.

be mapped to the 5QIs and vice versa. The TSN to 5G translation design is presented in Fig. 6.2(a), whereas its proof-of-concept implementation in OMNET++ is depicted in Fig. 6.2(b). The Ingress and Egress modules in the translator handle the reception and transmission of the message respectively. These two modules are realized in OMNeT++ with the egressTC and ingressTC submodules as shown in Fig. 6.2(b) respectively. The contents of the message received at the Ingress module are decapsulated by the Decapsulation module. Similarly, the message contents are encapsulated by the Encapsulation module before the message is transmitted by the Egress module. These two modules are realized by the IEtherEncap module in OMNET++. We introduce a new module, namely Tag Control Information (TCI) of the 802.1Q Header or 802.1Q/TCI Check module, after the Decapsulation module as shown in Fig. 6.2(a). The 802.1Q/TCI Check module checks the priority level of the message received from the TSN network. Based on the priority level, the QoS requirement is mapped to the 5QI reference established earlier.

The 5QI reference is a pre-configured XML document representing the parameters that should be configured in the logical TSN bridge. The 802.1Q/TCI Check module is realized in OMNeT++, as shown in Fig. 6.2(b). A QoS mapping algorithm is applied between the priority level of the TSN message and the default priority level parameter stored in the pre-configured XML document. As this implementation does not have access to a 5G medium, the translator instead configures the channel within the logical TSN bridge to act as a 5G medium. This is done in the Handle Channel sub-module as shown in Fig. 6.2 (a). The handleChannel module is realized in OMNeT++, before encapsulating the message contents by the IEtherEncap module as in Fig. 6.2

(b). The channel gets the 5QI parameters as listed in the 3GPP standardized delay-critical GBR Table 6.2. Once the channel is configured correctly, the translator then encapsulates the message and sends it over the channel.

Mapping a TSN QoS message to a 5QI requires a systematic technique to check its priority level and handle it via specific QoS references. In this regard, the translation from TSN to 5G and corresponding QoS mapping is discussed in Algorithm 1. The structure of a TSN message is shown in Fig. 6.3, where the first 24 bytes consists of a preamble, destination MAC (DST MAC) and source MAC (SRC MAC) [25]. The 802.1Q header contains the TCI which identifies the data fields that state how the message should be prioritized. Lastly, the Ethernet Type (ETH Type), the Payload (Data), and the CRC fields.

| 8 bytes | 6 bytes | 6 bytes | 4 bytes | 2 bytes | 46-1500 bytes | 4 bytes |
|---|---|---|---|---|---|---|
| Preamble | DST MAC | SRC MAC | 802.1Q HDR | ETH type | Payload | CRC |

**Figure 6.3:** TSN message structure.

To map the message to a 5QI, the message is de-encapsulated down to the 20th byte, i.e., the Preamble, DST MAC, and SRC MAC are identified. The next 16 bits correspond to the TPID field, which has the value of 0x8100 for a TSN message [25]. The next 3 bits represent the PCP field containing the TSN message's priority value (0-7). This field is part of a larger field called Tag Control Information (TCI), which also contains the Drop Eligible Indicator (DEI) and the VLAN Identifier (VID). However, in our prototype implementation, it is assumed that all packets are not dropable and belong to the same VID. This is done to reduce the number of parameters in the initial stages of the implementation. The structure of the 802.1Q Header Frame is shown in Fig. 6.4.

| 16 bits | 3 bits | 1 bit | 12 bits |
|---|---|---|---|
| TPID | TCI | | |
| | PCP | DEI | VID |

**Figure 6.4:** 802.1Q header frame structure.

Once the PCP value has been derived from the frame, it must be mapped to a 5QI. The TSN message is listed as a Delay-critical GBR [26] to pre-allocate dedicated network resources to TSN.

***2) 5G to TSN - Translation Flow:*** 5G utilizes GPRS Tunnelling Protocol (GTP) to encapsulate the frames sent over a tunnel. In the user-plane, the

**Algorithm 1** TSN to 5G translation flow

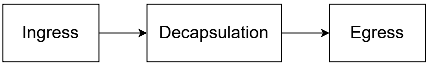
```
begin
  qosMapping_List $\leftarrow 5QIReferences$
  for all Messages_at_the_ingress_port do
      decapsulate down to the TPID
      decapsulate next 3 bits
      TCI_check PCP value in the TSN message
      assign 5QI to message.PCP
      handle_channel with the 5QI parameters
      encapsulate message
      send message_to_the_egress_port
  end for
end
```

GTP-U version is used [5]. The GPRS Tunnelling Protocol User Plane (GTP-U) frame structure is presented in Fig. 6.5. It starts with an outer header that specifies the source (SRC) and destination (DST) addresses. The QoS Flow Identifier (QFI) and the Tunnel Endpoint Identifier (TEID) are included in the GTP-U header. The QFI represents the priority level of the message, while the TEID indicates the tunnel ID for the PDU session anchor. Part of the 5G frame structure is also the IP message with its DST and SRC IP. In our case, the payload of the 5G GTP-U frame structure is indicated by the TSN frame that we aim to transmit over 5G.

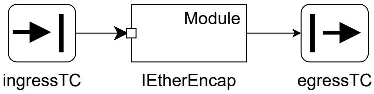
| Outer Header | | GTP-U Header | | IP-Package | | Payload |
|---|---|---|---|---|---|---|
| GTP-DST | GTP-SRC | QFI | TEID | IP-DST | IP-SRC | TSN-Frame |

**Figure 6.5:** 5G - GTP-U Frame Structure.

The 5G to TSN translation is done by decapsulating the frame, removing the GTP-U and IP Header, to make the frame function as a TSN frame again. The frame is then sent to the TSN bridge which can maintain the QoS by prioritising the frame appropriately depending on the PCP value. The 5G to TSN translation is graphically depicted in Fig. 6.6 and algorithmically presented in Algorithm 2.



(a) 5G to TSN Translation Flow.



(b) A proof-of-concept implementation of 5G to TSN Translation Flow in OMNeT++.

**Figure 6.6:** The translation flow between 5G and TSN networks.

**Algorithm 2** 5G to TSN translation flow

```
begin
  for all Messages_at_the_ingress_port do
      decapsulate down to the payload
      send message_to_the_egress_port
  end for
end
```

## 6.4 Simulation Development

In this section, we present our simulation development, starting with describing the simulation environment, and then explaining the simulation setup of a 5G node inside a TSN network environment. All the flow information is brought together to the finalized design implemented in OMNeT++/NeSTiNg. The source code for the developed TSN-5G simulator is openly provided in gitlab[3].

### 6.4.1 Simulation Environment - NeSTiNg

The OMNeT++ simulation environment offers ease of extension to incorporate various network protocols thanks to its modular architecture. The translation of traffic between 5G and TSN is implemented in OMNeT++ by leveraging NeSTiNg, which is a TSN simulation framework built over OMNeT++ [6]. NeSTiNg is built as an enhancement of the Ethernet protocol provided by

---

[3] `https://gitlab.com/DavidPantzar/5GTSNTranslator`

the INET framework. The main features of TSN supported by NeSTiNg are scheduling, gate control, queuing, and frame preemption.

To make full use of the simulation model, we perform a study on the capabilities and limitations of NeSTiNg. For scheduling of various traffic in TSN, NeSTiNg supports both Credit Based Shaper (CBS) and Time Aware Shaper (TAS) [6]. One of the main challenges in NeSTiNg is the lack of global simulation clock, which is needed as all TSN bridges are synchronized. NeSTiNg does not support the IEEE 802.1AS standard [27] for time synchronization in TSN networks. Furthermore, it neglects two major TSN implementations, which are IEEE 802.1CB Frame Replication and Elimination for Reliability (FRER) and IEEE 802.1Qci Per-Stream Filtering and Policing (PSFP).

### 6.4.2 Simulation Setup

The implementation is done in OMNeT++ by integrating modules and submodules into a network. Only some of the modules had to be re-written to fulfil the requirements of the translator: IEtherEncap and handleChannel. The 5G Node contains an Ethernet gate (ethg), the TSN-Translator (TT), and the message dispatcher between the two. It also has a few sub-modules including interfaceTable, filteringDatabase, scheduleSwap, oscillator, legacyClock, and the clock. The interface table and the filteringDatabase indicate where the traffic should go once it has been handled. The indication is done by establishing port and destination mapping rules in an XML document. The oscillator and clock modules deal with the time ticks in the modules and synchronize to the simulation time for time-stamping of logged data. A visual representation of the 5G node is shown in Fig. 6.7, where various entities indicate submodules, the horizontal line is the message dispatcher, and the arrows are channels connecting the modules. Note that the submodules shown on the left side of the horizontal line in Fig. 6.7 do not require any connectors and should be seen as a way to access information elsewhere in the system.

The line underneath the eth submodule leading to the module's border indicates the possibility of other modules, such as VlanEtherSwitchPreemptable (TSN Bridges), to connect to the 5G Node. Note that the arrows in the 5G node are bidirectional, i.e., both the TT and the eth modules can send and receive data. Each of the gates connects to a channel; this channel can be seen as a submodule with established parameters. They are initialized to default values, which can be changed during runtime. These parameters include delay of transfer, packet error rate, or data rate. One of the TSN-Translator (TT) functions is to configure these parameters of the channel to correct values to simulate the max-delay of the PDB to establish a simulated 5G transfer. Simi-

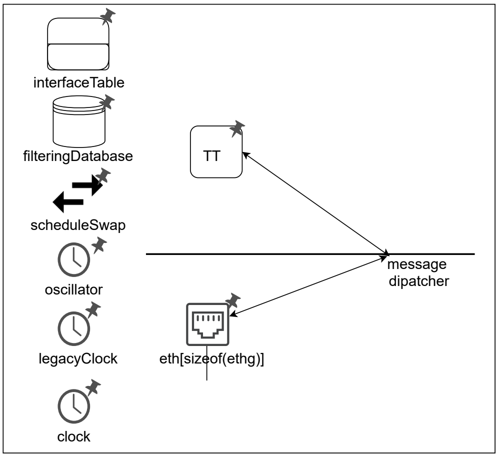


**Figure 6.7:** 5G Node in OMNeT++.

larly, as to how the QFI would change the parameters in an actual 5G node, the TT looks at the incoming transmissions PCP value and changes the channel parameters to pre-determined values that are set in the XML files.

***5QI - XML Integration:*** When the TT function is initialized, it collects the data structures of pre-determined QoS parameters of the channel in the XML file. The XML file also allows the users to establish these parameters beforehand. This XML file is akin to the 5QI values in an actual 5G node. As this proof-of-concept implementation of the translator focuses on the user-plane, an XML file loaded during initialization is an elegant solution. The loaded file contains the delay, data rate, and PER of the channel. The translator chooses the parameters that correspond to the PCP value being sent through the device. There are eight different levels of PCP in TSN. Hence, eight 5QIs can be used. The delayPar parameter sets the delay of the channel to the indicated value, the errorRatePar sets the packet error rate, and the dataratePar sets the datarate. A detailed description of the implementation in simulation environment is presented in [28].

## 6.5 Evaluation: Automotive Industrial Use Case

This section presents an industrial use case that is used to evaluate the proposed technique and its proof-of-concept implementation.

### 6.5.1 Use Case Setup

The use case is a part of an autonomous recycling site that contains several autonomous vehicles (recycling cranes and haulers). Each vehicle uses TSN for onboard backbone communication. The vehicles communicate with each other and with their remote control center using 5G. We consider a part of one of these vehicles and the remote control center as shown in Fig. 6.8.

There are four nodes that are connected to a TSN bridge within the vehicle. Similarly, there are two nodes that are connected to one TSN bridge in the remote control center. Within the vehicle, the actuator node (A) is controlled by a camera input that is acquired by node (S). The camera node is connected to an aggregation node (Agg) that performs aggregation of data and computation of control signals. The 5G gateway node (G1) is responsible for communicating with the 5G gateway node (G2) in the remote control center. The Remote Computer node (RC) in the remote control center computes the actuators' states in each vehicle. The visual representation of the use case in the simulation environment is depicted in Fig. 6.9.

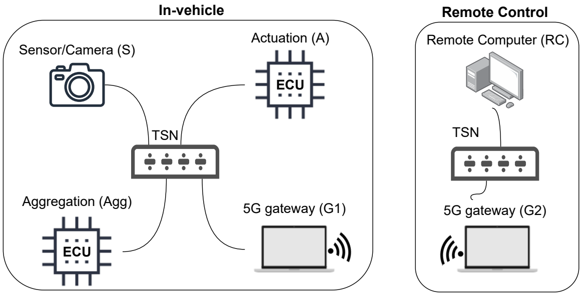


**Figure 6.8:** Automotive industrial use case utilizing TSN & 5G.

The traffic flow in the use case is as follows:

(S)–>(AGG)–>(G1)–>(G2)–>(RC)–>(G2)–>(G1)–>(A)

The node (S) sends its data to the (Agg) node that, in turn, sends the computed data to the (RC) node through the 5G network. The (RC) node then sends a message back to the vehicle through the 5G network to node (A). We focus on investigating the channel propagation delay in the message that originates from node (S) and terminates at the actuator node (A).

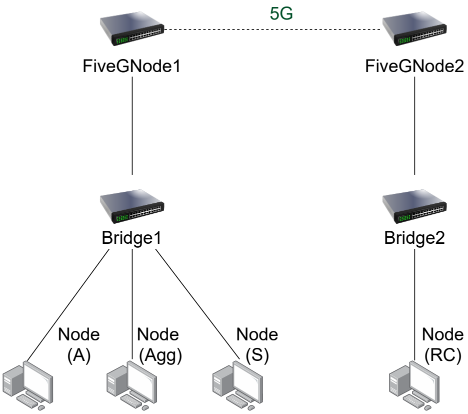


**Figure 6.9:** Model of the use case in the simulation mode.

### 6.5.2 Simulation Parameters

The simulation parameters are set either on the channels or in the omnetpp.ini file. Each wired channel has a 100Mbit/s bandwidth. The transmission delay of a TSN message with maximum payload (1546 Bytes) on each link is equal to $123\mu s$. The processing delay in each of the node (S), (Agg), (A) and (RC) is equal to $20\mu s$, while the processing delay in each of the nodes G1 and G2 is set to 0.5ms to simulate maximum latency of L2/L3 flow as per 3GPP to fulfil the URLLC requirements in the UP [29]. The 5G channel delay is set to the parameters indicated by the XML-file. The TSN bridges are set with a pre-configured offline schedule. The gates on the TSN bridges are set to StrictPriority, which indicates that they both check if a gate is open and the PCP value of the incoming traffic to determine which message to prioritize. The end-to-end deadline of the message of interest is 50ms according to the requirement specification of the use case.

### 6.5.3 Scheduling Parameters

The schedule used in this use case is created to showcase that the tool functions even with gates not being open at all times. The (S) and (Agg) assume the same priority and set their PCP values to 1, while the (RC) node has its traffic assigned to a PCP value of 2. Each of the devices is set with a period of 10ms and varying offsets depending on the arrival time of the previous message. For example, the message sending task in (RC) has an offset of 2500 $\mu s$. This offset corresponds to the time it takes for the message to arrive from the (Agg) node. Table 6.3 shows the period and offset of each of the task in the corresponding nodes. The scheduling sub-module was already part of the NeSTiNg packet in OMNeT++ and was derived from the simulation environment [6]. The schedule is designed so that the gates are open as the message arrives at Bridge1 but the gates open with a slight delay when a message arrives at Bridge2. This was done to simulate a potential configuration where other messages with different priorities go through the port. The scheduling works by having gates opened or closed for a certain length over a set cycle. The gates are represented by bit-vectors where the value '0' indicates the closed state of the gate, and the value '1' indicates that the gate has an open state.

**Table 6.3:** Scheduling parameters.

| **MessageID** | **Name** | **Start time ($\mu s$)** | **Period ( $\mu s$)** |
|---|---|---|---|
| 1 | Camera | 10 | 10000 |
| 2 | Aggregator | 300 | 10000 |
| 3 | Remote Control | 2500 | 10000 |

### 6.5.4 Evaluation Results

We focus on two main aspects in the evaluation: end-to-end delay and channel manipulation by the translator design during the run-time.

Fig. 6.10 shows the delay at each hop in the converged TSN-5G network depicted in Fig. 6.9. The horizontal axis shows the events that are explained in Table 6.4. For example, event 1 shows the processing delay in Node (S). Similarly, event 17 shows the delay of the message received in Node (A). The vertical axis in Fig. 6.10 shows the cumulative delay at various events with respect to the start of the flow (Node (S) sensing the values). The blue line indicates the measured cumulative delay for each event in the simulator, while the highlighted red values represents the cumulative delay for the flow: Node (S) -> Node (Agg) -> Node (RC) -> Node (A). For example, the cumulative delay from sensor Node (S) to aggregator Node (Agg) is 0.27ms. The end-to-end delay from the sensor (Node (S)) to the actuator (Node (A)) in the traffic flow in the use case in Fig. 6.8 is 5.57ms.

It is interesting to not that there are considerable jumps in the delay between the events 6 and 7 and between the events 13 to 14. These jumps show the transmission time over the 5G channel with the slight difference between each due to the different priority level used to manipulate the 5G channel as described below.

The manipulation of the channel is indicated by first writing the PCP value and then the corresponding XML value, shown by an output of XMLInfo as depicted in Fig. 6.11. To make sure that the values are properly configured,

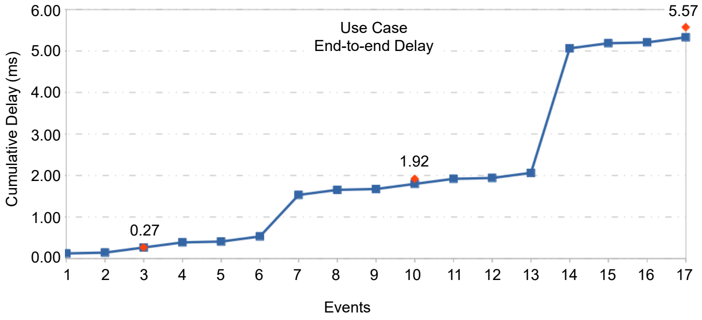


**Figure 6.10:** End-to-end delay in the automotive use case.

**Table 6.4:** Representation of each event included in the transmission flow from Sensor to Actuator.

| Event | Event Interpretation |
|---|---|
| 1 | Processing delay in Node (S) |
| 2 | Transmission delay between Node (S) and Bridge1 |
| 3 | Transmission delay between Bridge1 and Node (Agg) |
| 4 | Node (Agg) sends the message back to Bridge1 |
| 5 | Translation delay from TSN to 5G |
| 6 | The message is sent to the FiveGNode1 |
| 7 | Transmission delay from FiveGNode1 to FiveGnode2 (PCP 1) |
| 8 | Translation delay from 5G to TSN |
| 9 | The message is sent to Bridge2 |
| 10 | Bridge2 sends the message to Node (RC) |
| 11 | Node (RC) sends the message back to Bridge2 |
| 12 | Translation delay from TSN to 5G |
| 13 | The message is sent to the FiveGNode2 |
| 14 | Transmission delay from FiveGNode2 to FiveGnode1 (PCP 2) |
| 15 | Translation delay from 5G to TSN |
| 16 | The RC message is sent to Bridge1 |
| 17 | Bridge1 sends the RC message to Node (A) |

the channel parameters are also output to the console. This flow of output can be seen in Fig. 6.11 which shows how different PCP values provide different outputs and corresponding channel delay.

PCP 1 is used from Node (Agg) to Node (RC) and is indicated by events 6 to 7. Similarly, PCP 2 is used from Node (RC) to Node (A) and is denoted by

```
INFO: PCPValue: 1
INFO: XMLInfo: Delay: 0.001
INFO: XMLInfo: PER: 0.0001
INFO: XMLInfo: Datarate: 100000000
INFO: Channel Delay: 0.001
INFO: Channel PER: 0.0001
INFO: Channel Datarate: 1e+08
```

**(a)**

```
INFO: PCPValue: 2
INFO: XMLInfo: Delay: 0.003
INFO: XMLInfo: PER: 0.0001
INFO: XMLInfo: Datarate: 100000000
INFO: Channel Delay: 0.003
INFO: Channel PER: 0.0001
INFO: Channel Datarate: 1e+08
```

**(b)**

**Figure 6.11:** 5G channel manipulation based on different priority levels: a) PCP 1 output for message sent from Node (Agg) to Node (RC), and b) PCP 2 output for message sent from Node (RC) to Node (A).

events 13 to 14. In Fig. 6.11, the PCP value is first read and then matched to the PCPValue of the XML document as listed by the XMLInfo. This is applied to the channel, indicated by the Channel Delay, PER, and Datarate. For PCP 1 and 2, the delays of 0.001s and 0.003s correspond to the delay-time increase when looking at events 6 to 7, and 13 to 14.

The parameters' values for each PCP correspond to the predefined values in the XML file. This shows that the translator performed well on channel manipulation during run-time. The use case shows a change in channel parameters depending on the read PCP value and is, therefore, the first step towards an improved converged TSN-5G network within the NeSTiNg simulation tool.

## 6.6 Conclusions

In this paper, we proposed a technique to integrate TSN and 5G communication mainly focusing on the translation of the flows between them. Furthermore, we presented a proof-of-concept implementation of the proposed technique in a commonly used free simulation tool, namely NeSTiNg. We utilized an automotive industrial use case to evaluate the performance of the proposed technique and the simulator. We showed that the proposed technique can be useful for the network designers to evaluate TSN-5G heterogeneous network configurations with regards to end-to-end delays.

The current implementation in the simulator assumes that the clock synchronization is perfect between the devices in use. This is not the case in a real-world scenario where TSN and 5G have their clock synchronization schemes. The sharing of time information between the TSN and 5G system is a required step for a fully synchronized system. Therefore, an important step forward is to design and implement such a synchronization. Moreover, other features of 5G according to URLLC can be integrated, which entails another future work.

## Acknowledgment

The work in this paper is supported by the Swedish Governmental Agency for Innovation Systems (VINNOVA) via the PROVIDENT project and by the Swedish Knowledge Foundation via the projects DPAC & HERO. We thank all our industrial partners, especially Arcticus Systems & HIAB.

# Bibliography

[1] Joachim Sachs, Kenneth Wallstedt, Fredrik Alriksson, and Göran Eneroth. Boosting smart manufacturing with 5G wireless connectivity. Ericsson Technology Review, February 2019. [Online]. Available: `https://www.ericsson.com/49232f/assets/local/reports-papers/ericsson-technology-review/docs/2019/5g-and-smart-manufacturing.pdf`.

[2] Saad Mubeen, Pavlos Nikolaidis, Alma Didic, Hongyu Pei-Breivold, Kristian Sandström, and Moris Behnam. Delay Mitigation in Offloaded Cloud Controllers in Industrial IoT. *IEEE Access*, 5:4418–4430, 2017.

[3] HMS. Industrial Ethernet is now bigger than fieldbuses, February 2018. [Online]. Available: `https://www.hms-networks.com/news-and-insights/2018/02/27/industrial-ethernet-is-now-bigger-than-fieldbuses`.

[4] Mohammad Ashjaei, Lucia Lo Bello, Masoud Daneshtalab, Gaetano Patti, Sergio Saponara, and Saad Mubeen. Time-Sensitive Networking in automotive embedded systems: State of the art and research opportunities. *Journal of Systems Architecture*, 117:102137, 2021.

[5] Technical Specification Group Services and System Aspects; System architecture for the 5G system (5GS)(Release 16). Technical report, 3GPP TS 23.501, 10 2020.

[6] Jonathan Falk, David Hellmanns, Ben Carabelli, Naresh Nayak, Frank Dürr, Stephan Kehrer, and Kurt Rothermel. Nesting: Simulating IEEE Time-Sensitive Networking (TSN) in OMNeT++. In *2019 International Conference on Networked Systems*, pages 1–8, 2019.

[7] Lucia Lo Bello and Wilfried Steiner. A perspective on IEEE Time-sensitive Networking for Industrial Communication and Automation Systems. *Proceedings of the IEEE*, 107(6):1094–1120, 2019.

[8] Lucia Lo Bello, Riccardo Mariani, Saad Mubeen, and Sergio Saponara. Recent Advances and Trends in On-Board Embedded and Networked Automotive Systems. *IEEE Transactions on Industrial Informatics*, 15(2):1038–1051, 2019.

[9] Bahar Houtan, Mohammad Ashjaei, Masoud Daneshtalab, Mikael Sjödin, and Saad Mubeen. Synthesising schedules to improve qos of

best-effort traffic in tsn networks. In *29th International Conference on Real-Time Networks and Systems (RTNS)*, April 2021.

[10] Imtiaz Parvez, Ali Rahmati, Ismail Guvenc, Arif I. Sarwat, and Huaiyu Dai. A Survey on Low Latency Towards 5G: RAN, Core Network and Caching Solutions. *IEEE Communications Surveys Tutorials*, 20(4):3098–3130, 2018.

[11] Jeffrey G. Andrews, Stefano Buzzi, Wan Choi, Stephen V. Hanly, Angel Lozano, Anthony C. K. Soong, and Jianzhong Charlie Zhang. What will 5G be? *IEEE Journal on Selected Areas in Communications*, 32(6):1065–1082, 2014.

[12] Shanshan Zhao Shancang Li, Li Da Xu. 5G internet of things: A survey. *Journal of Industrial Information Integration*, 10:1–9, 2018.

[13] Godfrey Anuga Akpakwu, Bruno J. Silva, Gerhard P. Hancke, and Adnan M. Abu-Mahfouz. A Survey on 5G Networks for the Internet of Things: Communication Technologies and Challenges. *IEEE Access*, 6, 2018.

[14] M. A. Siddiqi, H. Yu, J. Joung. 5G ultra-reliable low-latency communication implementation challenges and operational issues with IoT devices, September 2019.

[15] Mikko Säily, Carlos Barjau Estevan, Jordi Joan Gimenez, Fasil Tesema, Wei Guo, David Gomez-Barquero, and De Mi. 5G Radio Access Network Architecture for Terrestrial Broadcast Services. *IEEE Transactions on Broadcasting*, 66(2):404–415, 2020.

[16] A. Zaidi, A. Bränneby, A. Nazari, M. Hogan, and C. Kuhlins. Cellular IoT in the 5G era: Realizing cellular IoT for industrial transformation, June 2019. [Online]. Available: https://www.ericsson.com/en/reports-and-papers/white-papers/cellular- iot-in-the-5g-era.

[17] Istvan Godor, Michele Luvisotto, Stefano Ruffini, Kun Wang, Dhruvin Patel, Joachim Sachs, Ognjen Dobrijevic, Daniel P. Venmani, Olivier Le Moult, Jose Costa-Requena, Aapo Poutanen, Chris Marshall, and Janos Farkas. A Look Inside 5G Standards to Support Time Synchronization for Smart Manufacturing. *IEEE Communications Standards Magazine*, 4(3):14–21, 2020.

[18] Maximilian Schüngel, Steven Dietrich, David Ginthör, Shun-Ping Chen, and Michael Kuhn. Analysis of time synchronization for converged wired

and wireless networks. In *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, volume 1, pages 198–205, Vienna, Austria, 2020. IEEE.

[19] Technical Specification Group Services and System Aspects; Study on enhancement of 5G System (5GS) for vertical and Local Area Network (LAN) services (Release 16). Technical report, 3GPP TR 23.734, 06 2019.

[20] Bernd Holfeld, Dennis Wieruch, Thomas Wirth, Lars Thiele, Shehzad Ali Ashraf, Jorg Huschke, Ismet Aktas, and Junaid Ansari. Wireless Communication for Factory Automation: an opportunity for LTE and 5G systems. *IEEE Communications Magazine*, 54(6):36–43, 2016.

[21] Maximilian Schüngel, Steven Dietrich, David Ginthör, Shun-Ping Chen, and Michael Kuhn. Single Message Distribution of Timing Information for Time Synchronization in Converged Wired and Wireless Networks. In *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation*, volume 1, pages 286–293, 2020.

[22] OMNEST. [Online]. Available: https://omnest.com/.

[23] David Ginthör, Johannes von Hoyningen-Huene, Rene Guillaume, and Hans Schotten. Analysis of Multi-user Scheduling in a TSN-enabled 5G System for Industrial Applications. In *2019 IEEE International Conference on Industrial Internet (ICII)*, pages 190–199, 2019.

[24] Lukas Martenvormfelde, Arne Neumann, Lukasz Wisniewski, and Jürgen Jasperneite. A Simulation Model for Integrating 5G into Time Sensitive Networking as a Transparent Bridge. In *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation*, volume 1, pages 1103–1106, 2020.

[25] Cisco. Inter-Switch Link and IEEE 802.1Q Frame Format. [Online]. Available: https://www.cisco.com/c/en/us/support/docs/lan-switching/8021q/17056-741-4.html".

[26] Ana Larrañaga, M. Carmen Lucas-Estañ, Imanol Martinez, Iñaki Val, and Javier Gozalvez. Analysis of 5G-TSN Integration to Support Industry 4.0. In *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, volume 1, pages 1111–1114, Vienna, Austria, 2020. IEEE.

[27] Michael D. Johas Teener and Geoffrey M. Garner. Overview and timing performance of IEEE 802.1AS. In *2008 IEEE International Symposium on Precision Clock Synchronization for Measurement, Control and Communication*, pages 49–53, 2008.

[28] Alexander Magnusson and David Pantzar. Integrating 5G Components into a TSN Discrete Event Simulation Framework. Master Thesis, School of Innovation, Design and Engineering, Mälardalen University, Sweden, 2021.

[29] Technical Specification Group Services and System Aspects; Study on Scenarios and Requirements for Next Generation Access Technologies (Release 14). Technical report, 3GPP Rep. 38.913, 2017.

# Chapter 7

# Paper C: QoS-MAN: A Novel QoS Mapping Algorithm for TSN-5G Flows

Zenepe Satka, Mohammad Ashjaei, Hossein Fotouhi, Masoud Daneshtalab, Mikael Sjödin, Saad Mubeen.
In the $28^{th}$ 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 based on the application constraints used 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.

## 7.1 Introduction

Many contemporary industrial communication systems are based on wired Ethernet networks. Despite having many advantages, these networks suffer from low flexibility and have high installation and maintenance costs [1]. These shortcomings of wired networks in industrial systems have paved way for wireless communication networks, like WIFI, 4G and 5G, to mention a few. In a wireless communication system, various devices strive to link with each other in a limited capacity of radio spectrum [2]. The advancement in modern wireless and cellular communication technologies have expanded the capacity and coverage of industrial communication systems.

The advantages of both wired and wireless networks can be utilized in industrial communication systems by integrating these networks in a unified heterogeneous wired/wireless network. In such a network, each (sub) network may implement a different protocol and may have different Quality of Service (QoS) characteristics of the underlying flows. In order to achieve a seamless and unified heterogeneous network, the QoS characteristics of the flows need to be systematically mapped in-between different (sub) networks [3], [4]. The estimation of end-to-end QoS of flows in such networks is a critical challenge [5]. One way to measure the overall performance of heterogeneous networks is by quantifying the effects of each participating application and access technology [6].

The fifth generation of mobile networks (5G), as defined by the 3rd generation partnership project (3GPP)[1], support multiple broadband networks providing end-to-end QoS guarantees. The 3GPP Releases define standardized QoS classes/profiles for different services' needs, which makes the mapping of QoS classes over heterogeneous networks a daunting task [3]. Time-Sensitive Networking (TSN) is a set of standards based on switched Ethernet[2] that supports high-bandwidth and low-latency wired communication [7, 8]. On the other hand, 5G offers promising solution to support ultra-reliable low latency communication (URLLC) [9]. The integration of TSN and 5G would provide greater level of flexibility in the network communication, while supporting the high-bandwidth and low-latency communication needs of many industrial communication systems that utilize both wired and wireless networks. Alas, the 3GPP specifications do not define a mapping of QoS attributes between 5G and TSN. Defining such a mapping in a systematic way is a non-trivial task and has a profound impact on the end-to-end QoS experienced by the traffic flows in a heterogeneous TSN-5G network.

---

[1] https://www.3gpp.org/

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

In this paper, we propose a novel algorithm, called the QoS-MAN, to systematically 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 considered 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 strict QoS.

The main contributions in this paper are as follows:

1. We introduce an efficient QoS mapping algorithm that systematically maps TSN traffic flows or any Ethernet-based traffic flows to different 5G QoS flows, using the QoS characteristics standardized in the 3GPP Release 16 [10]. To the best of our knowledge, this is the first work that systematically maps the flows between Ethernet and 5G network domains using a QoS-aware mapping algorithm.

2. To evaluate the proposed algorithm, we generate synthetic scenarios with random sets of applications' constraints to show how the algorithm performs with respect to fulfilling the applications' constraints.

The rest of the paper is organized as follows. Section 7.2 presents the background and related work. The proposed mapping algorithm is presented in Section 7.3, while Section 7.4 provides evaluation and results. Finally, the conclusion and future work are presented in Section 7.5.

## 7.2 Background and Related Work

### 7.2.1 5G network

Each 5G user equipment establishes a Packet Data Unit (PDU) similar to the concept of a Packet Data Network (PDN) connection in 4G, thus we describe the PDU session details and traffic flow management. 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 PDU session through the User Plane Function (UPF), containing up to 64 QoS flows. A UE may also request to establish multiple PDU Sessions in parallel [11], e.g, when a UE wants to use both Internet connectivity as well as IMS services at the same time. A 5G QoS flow is assigned to every flow or packet 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-GBR QoS flows. 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 [12].

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 [13]. 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 also shown in Fig. 7.1. Another mapping is performed on the radio side, assigning QoS flows to Data Radio Bearers (DRB). However, this type of mapping is beyond the scope of this work.

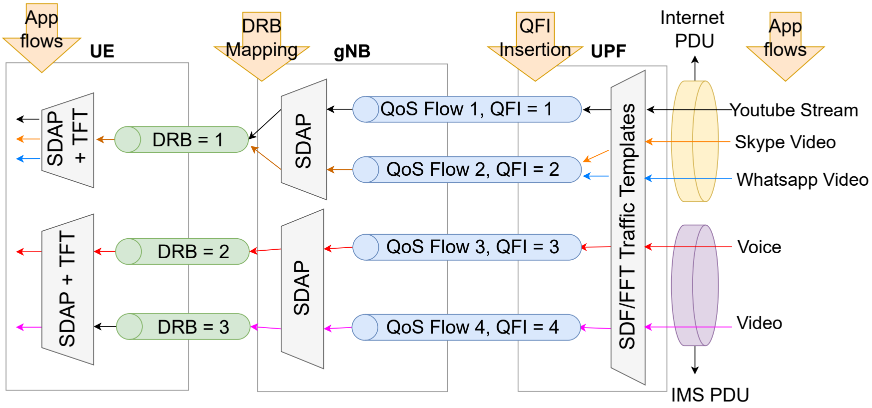


**Figure 7.1:** Example of QoS realization for downlink packets [14].

### 7.2.2 Traffic Forwarding and Traffic Classes in TSN

TSN is a set of standards developed to support high-bandwidth and low-latency communication over switched Ethernet. TSN switches support 8 different priorities defined by Priority Code Point (PCP) field. The PCP is a 3-bit value added in the 802.1Q-2018 VLAN tag. There are two scheduling mechanisms available in TSN: (i) Credit-based shaper for Audio-Video Bridging (AVB), and (ii) Time-Aware Shaper (TAS), which allows arbitration of traffic at the egress port. Each queue is controlled by a Gate Control List (GCL) where all the offline schedule is timestamped.

TSN supports three different traffic classes: Scheduled Traffic (ST), Audio Video Bridging with Class A and Class B, and BE traffic. The ST class is scheduled offline, with strict temporal isolation achieved with the TAS mechanism controlled by the GCL [15]. The GCL is pre-defined 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 priority classes, class A and B, with A as the highest priority queue. The AVB traffic queues are controlled by the CBS mechanism [16]. The CBS works on credit basis, 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.

### 7.2.3 Related Work

There are several QoS mapping techniques between different network protocols that have been proposed in the literature. These works are categorized based on the mapping between parameters and traffic classes in each network protocol. In this section, we present an overview of the existing mapping techniques between different networks.

Satka et al. [17] developed a translation technique between TSN and 5G frames by mapping the default priority value of a 5G frame to the Priority Code Point (PCP) value of a TSN frame, and vice versa. The QoS-MAN algorithm considers this technique as an input. In comparison, QoS-MAN considers the entire set of predefined 5G QoS parameters, and instead of mapping those parameters to the priority levels of TSN frames, it elaborates further on the applications' requirements such as deadline, jitter, bandwidth, and packet loss. Al-Shaikhli et. al [3] propose a mapping framework for end-to-end QoS support over heterogeneous networks. The mapping framework consists of two scheduling policies: (i) a Class-Based Weighted Fair Queuing (CBWFQ) policy and (ii) a Rate-Controlled Priority Queuing (RCPQ) policy. The authors provide classification of the incoming traffic into appropriate QoS classes based on application's type and QoS requirements (latency, packet loss rate, bandwidth) similar to our work.

The work in [18] presents an effective QoS mapping method between the 5G QoS flow and the time and wavelength-division-multiplexed passive optical network (TWDM-PON) priority queue. TWDM-PON supports queue oriented QoS management introducing high, medium and low priority queues. This work maps the 5G QoS identifiers (22 in total) to the priority queues of PON based on the delay tolerance of services. The network load is also considered as it can affect the mapping relationship, e.g, when the traffic load is small, the backhaul network has more free resources to handle more priority queues. In addition, Zhang et.al [19] present a QoS-aware dynamic scheme to realize the interconnection between 5G and TSN networks. Differently from our work, they focus on the Virtual Network Function (VNF) mapping problems. They propose VNF mapping considering mixed integer linear programming with time-sensitive constraints together with a heuristic algorithm for VNF mapping and scheduling in the 5G-TSN network. Yang et al. [20] propose a scheme for low-latency transmission and resource management in a TSN-5G system. They include a QoS mapping table of TSN QoS information and 5G QoS Identifier (5QI) mapping table. This work focuses on uplink transmission schemes based on configured grant scheduling instead of mapping QoS containers in order to satisfy delay requirements of the applications.

Reviewing the existing works on QoS mapping algorithms, we observe that none of them support mapping TSN traffic into 5G. In this paper, we present such an algorithm and we show that the proposed algorithm, supports traffic mapping of Ethernet in general, but specifically TSN traffic to 5G traffic.

## 7.3 Proposed QoS Mapping for TSN-5G Flows

Traversing traffic from TSN to 5G requires a mapping from TSN QoS to 5G QoS. This mapping provides an appropriate forwarding treatment to TSN traffic inside the 5G system. In this section, first we define the QoS parameters and characteristics in 5G. Then we present the proposed mapping algorithm that can map not only TSN but also other Ethernet traffic to 5G flows based on the application's requirements.

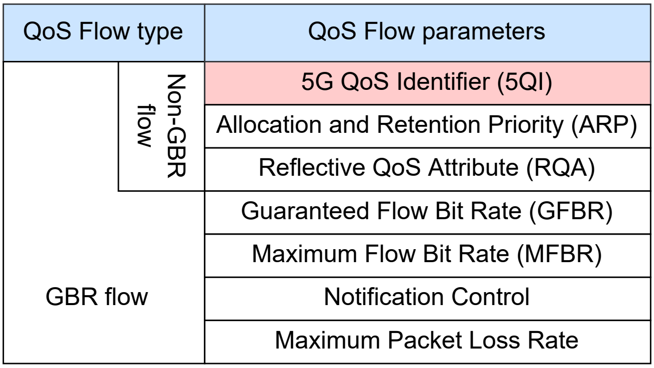
### 7.3.1 5G QoS Parameters and characteristics

The 5G QFI is a reference to a set of QoS parameters depending on the type of 5G QoS flow. This set of QoS Parameters is presented in Fig. 7.2. The focus of this paper is on 5G QoS Identifier (5QI). The detailed information for other QoS parameters from Fig. 7.2 can be found in [10].

5QI is a scalar referencing to a set of predefined QoS characteristics, as shown in Fig. 7.3. The 3GPP Release 16 [10] provides predefined values for each characteristic based on the type of service that is used.

The set of characteristics includes:

- *Resource Type:* it determines whether dedicated resources are pre-allocated to a QoS flow in a radio base station. The flows can be Guaranteed Bit Rate



| QoS Flow type | | QoS Flow parameters |
|---|---|---|
| GBR flow | Non-GBR flow | 5G QoS Identifier (5QI) |
| | | Allocation and Retention Priority (ARP) |
| | | Reflective QoS Attribute (RQA) |
| | | Guaranteed Flow Bit Rate (GFBR) |
| | | Maximum Flow Bit Rate (MFBR) |
| | | Notification Control |
| | | Maximum Packet Loss Rate |

**Figure 7.2:** 5G QoS flow types and their parameters.

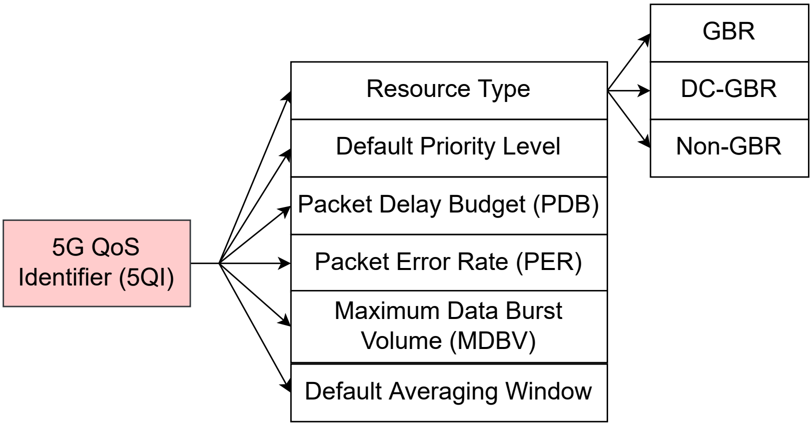


**Figure 7.3:** Standardized 5G QoS Characteristics.

(GBR), Delay-critical Guaranteed Bit Rate (DC-GBR), or Non-Guaranteed Bit Rate (Non-GBR). There are no pre-allocated resources for Non-GBR flows. On the other hand, GBR and DC-GBR flows are typically authorized “on demand", with the only difference that for DC-GBR, 3GPP specifies an extra characteristic, namely the Maximum Data Burst Volume, which will be described below.

- *Default Priority Level:* it indicates priority level of QoS flows. The smaller the number the higher the priority level.

- *Packet Delay Budget (PDB):* it defines an upper bound on the time a packet is delayed between UE and UPF. It is basically the time a packet can spend inside 5G system without being dropped.

- *Packet Error Rate (PER):* it defines an upper bound on the rate of packet losses, which is formally defined as the number of packets that have been sent by a link layer protocol, yet they could not be successfully delivered to the corresponding receiver.
- *Default Maximum Data Burst Volume:* it defines the largest amount of data that the 5G Radio Access Network is required to transmit within the PDB period.
- *Default Averaging Window:* it indicates the duration of time to calculate the GFBR and MFBR.

### 7.3.2 QoS-MAN algorithm

We propose a QoS Mapping Algorithm, called the QoS-MAN, to efficiently map Ethernet traffic flows to 5G QoS flows. The QoS-MAN algorithm uses application constraints and requirements, which can be defined for TSN or other Ethernet-based network flows. For the sake of simplicity, we divide our algorithm into two phases. In the first phase, the algorithm maps the Ethernet traffic flows to 5G resource types. Whereas in the second phase, the algorithm maps the traffic flows to specific 5G QoS Identifiers. The two phases are described in detail below.

#### Phase 1 – Mapping to 5G resource types

5G provides three types of resources, namely DC-GBR, GBR, and Non-GBR. Mapping TSN traffic flows to 5G QoS flows consists of mapping TSN traffic classes to 5G resource type that best fits to the TSN traffic needs. First, we present a naive mapping technique to map the TSN traffic classes to 5G resource types. As the ST traffic in TSN is fully deterministic with zero jitter on delivery of packets, it should be mapped to DC-GBR flows on a 5G system. The DC-GBR flows in 5G are authorized on demand using permanently pre-allocated resources, thus providing real-time guarantees on a PDB period with a MDBV.

AVB traffic in TSN is relatively less critical than ST traffic. Therefore, this traffic may or may not have hard real-time requirements. However, it still needs pre-allocation of radio resources to prevent suffering from lack of resources at any point in time. The GBR flows provide such guarantees. Therefore, AVB traffic is mapped to the GBR resource type.

The BE traffic in TSN is commonly referred to as non-critical traffic with no real-time requirements. Hence, this traffic is mapped to the Non-GBR flows in the 5G network. The naive mapping technique can be presented as follows.

$$\begin{gathered} \textit{DC-GBR} \longleftarrow \textit{ST} \\ \textit{GBR} \longleftarrow \textit{AVB} \\ \textit{Non-GBR} \longleftarrow \textit{BE} \end{gathered}$$

However, the naive technique of mapping TSN and 5G flows, discussed above, neither ensures any specific QoS for the packets nor fulfillment of the application's constraints. Instead, the technique only maps the packets based on their traffic class, e.g, AVB class can consist of critical data with real-time requirements that needs to be distinguished from other AVB traffic with no criticality or real-time requirements. The naive mapping technique maps all such AVB traffic in a similar fashion to the 5G flows regardless of the real-time requirements. Another limitation of the naive mapping technique is that it does not consider the bandwidth or packet loss rate constraints of an application while performing the mapping between TSN and 5G flows.

In order to deal with the above mentioned limitations of the naive mapping technique, we present an extended technique by developing three logic-based equations for each type of resource. The technique uses the application requirements as its input. We define these requirements in the form of constraints such as the Deadline constraint (DL), Jitter constraint on delivery of packets (JO), and Bandwidth constraint (BW). All parameters are treated as Boolean variables. A non-zero parameter means that the application has a requirement on that specific parameter, otherwise the application does not impose any requirement on the parameter. The algorithm first checks if the application has real-time requirements or not. In this work, these requirements correspond to the deadline or jitter constraints on the packets send by the application.

An application is assigned a Non-Guaranteed Bit Rate (Non-GBR) resource if it does not have any real-time requirement on the reception of flows.

$$\textit{Non-GBR} = !\ (\textit{DL} \,\|\, \textit{JO})$$

If an application has real-time requirements (deadline, jitter or both) but does not have bandwidth constraints, then the Guaranteed Bit Rate (GBR) flow type is assigned to it. However, if an application has real-time requirements as well as constraints on the throughput or bandwidth, then it is assigned the Delay-Critical Guaranteed Bit Rate (DC-GBR) resource type.

$$\begin{gathered} \textit{GBR} = (\textit{DL} \,\|\, \textit{JO})\ \&\ !(\textit{BW}) \\ \textit{DC-GBR} = (\textit{DL} \,\|\, \textit{JO})\ \&\ \textit{BW} \end{gathered}$$

We summarize the mapping equations with a truth table shown in Table 7.1, where 1 identifies availability of the constraint, while 0 identifies otherwise. Note that $X$ shows that the constraint can have any binary value.

The pseudocode of QoS-MAN algorithm is presented in Algorithm 3. This algorithm takes the number of applications and applications' constraints

**Table 7.1:** Truth table of the mapping technique.

| DL | JO | BW | GBR | DC-GBR | Non-GBR |
|---|---|---|---|---|---|
| 0 | 0 | X | 0 | 0 | 1 |
| 0 | 1 | 0 | 1 | 0 | 0 |
| 0 | 1 | 1 | 0 | 1 | 0 |
| 1 | 0 | 0 | 1 | 0 | 0 |
| 1 | 0 | 1 | 0 | 1 | 0 |
| 1 | 1 | 0 | 1 | 0 | 0 |
| 1 | 1 | 1 | 0 | 1 | 0 |

(i.e., Deadline, Jitter, Bandwidth, and Packet Error Rate) as inputs, and maps them to different 5G resource types using the logical equations presented above. The functions $MappingToDC(i)$, $MappingToGBR(i)$, and $MappingToNonGBR(i)$ will be described in Phase 2.

**Algorithm 3** QoS-MAN algorithm.

```
begin
$n \leftarrow number\_of\_apps$
$applicationRequiements \leftarrow user\_input$
$NonGBR\_matrix \leftarrow predefined\_NonGBRqos$
$GBR\_matrix \leftarrow predefined\_GBRqos$
$DC\_GBR\_matrix \leftarrow predefined\_DC\_GBRqos$
for $application[i]$ where $i \leftarrow 1$ to $n$ do
    if $app[i].Deadline || app[i].Jitter$ then
        if $app[i].Bandwidth$ then
            $QoS[i].resourceType \leftarrow DelayCriticalGBR$
            MappingToDC(i)
            return $QosProfile[i]$
        else
            $QoS[i].resourceType \leftarrow GBR$
            MappingToGBR(i)
            return $QosProfile[i]$
        end if
    else
        $QoS[i].resourceType \leftarrow Non\_GBR$
        MappingToNonGBR(i)
        return $QosProfile[i]$
    end if
end for
end
```

### Phase 2 – Mapping to 5G QoS identifiers

For each type of resource, the 3GPP Release 16 [10] defines a set of values for QoS characteristics, i.e., PDB, PER, MDBV, as described in Section 7.2. A 5G QoS Identifier is used as a reference to the predefined values of QoS characteristics. In our approach, 5QI is equivalent to QoS Flow Identifier (QFI), used as a unique value to identify the QoS flow. There are 5 possible QFI-s for DC-GBR, 12 QFIs for GBR, and 9 QFI-s for Non-GBR as shown in Tables 7.2, 7.3, and 7.4 used as an input to the QoS-MAN algorithm. Phase 2 of the algorithm efficiently assigns QFIs to specific traffic flows based on the values of deadline, bandwidth and packer error rate, if any.

The 3GPP Release 16 defines the information for DC-GBR resources presented in Table 7.2, where the Guaranteed Bandwidth is calculated by dividing the Maximum Data Burst Volume (MDBV) with the Packet Delay Budget (PDB):

$$BW = \frac{MDBV}{PDB}$$

**Table 7.2:** QFIs for standardized Delay-Critical GBR flows.

| **QoS/ QFI** | **Priority** | **Guaranteed Bandwidth (Mbit/s)** | **Packet Error Rate (PER)** |
|---|---|---|---|
| 86 | 18 | 2.1664 | $10^{-4}$ |
| 82 | 19 | 0.204 | $10^{-4}$ |
| 85 | 21 | 0.408 | $10^{-5}$ |
| 83 | 22 | 1.0832 | $10^{-4}$ |
| 84 | 24 | 0.361 | $10^{-4}$ |

Algorithm 4 uses the predefined values from Table 7.2 to map traffic flows to specific QFIs based on the application's bandwidth constraint.

**Algorithm 4** *MappingToDC(i)*

```
begin
 1: $i \leftarrow applicationID$
 2: $QoSBW \leftarrow findClosestBW(DC\_BW, 5, app[i].BW)$
 3: for $k \leftarrow 0$ to $4$ do
 4:     if $DC\_GBR[k][1] == QoSBW$ then
 5:         $QoS[i].identifier \leftarrow DC\_GBR[k][0]$
 6:         $break;$
 7:     else
 8:         $QoS[i].identifier \leftarrow 500$
 9:     end if
10: end for
end
```

Algorithm 4 takes the application's bandwidth and compares it to guaranteed bandwidth values from Table 7.2, defining the closest higher guaranteed bandwidth depicted as QoSBW - line 2 of Algorithm 4. Then, the traffic flow is assigned to the identifier that assures the specific QoSBW that best fulfills the application's requested bandwidth, and exits the loop. If there is no QFI which assures the requested bandwidth then we assign the application to a non-significant QFI (500) saying that the algorithm failed to fulfill the application's BW using the standardized DC-GBR flows.

To map traffic flows to QoS flows of GBR resource type, we use the values of the standardized QoS characteristics' from 3GPP shown in Table 7.3.

**Table 7.3:** QFIs for standardized GBR flows.

| QoS/ QFI | Priority | Packet Delay Budget (PDB)(ms) | Packet Error Rate (PER) |
|---|---|---|---|
| 3 | 30 | 50 | $10^{-3}$ |
| 65 | 7 | 75 | $10^{-2}$ |
| 67 | 15 | 100 | $10^{-3}$ |
| 1 | 20 | 100 | $10^{-2}$ |
| 66 | 20 | 100 | $10^{-2}$ |
| 2 | 40 | 150 | $10^{-3}$ |
| 71 | 56 | 150 | $10^{-6}$ |
| 4 | 50 | 300 | $10^{-6}$ |
| 72 | 56 | 300 | $10^{-4}$ |
| 73 | 56 | 300 | $10^{-8}$ |
| 74 | 56 | 500 | $10^{-8}$ |
| 76 | 56 | 500 | $10^{-4}$ |

The QoS-MAN algorithm takes these values as an input to effectively choose the right QFI value for the traffic flow of each application as shown in Algorithm 5. First, the algorithm searches column 3 in Table 7.3 to find the PDB value that is closest to (but lower than) the deadline constraint of each application depicted as QoSPDB - line 2 of Algorithm 5. From Table 7.3 one can notice that there are many identifiers that have the same PDB value but have different PERs. To better assign the QFI, in line 5 of Algorithm 5 we make sure that the algorithm selects the QFI that assures a PER greater than or equal to the application's PER constraint, and exits the loop. If the application's constraints (PER, PDB) cannot be assured from the GBR Qos then we assign a non-significant (400) identifier saying that the algorithm failed to assign this application to a GBR QoS flow.

**Algorithm 5** *MappingToGBR(i)*

```
begin
 1: $i \leftarrow applicationID$
 2: $QoSPDB \leftarrow findClosest(GBR\_PDB, 12, app[i].DL)$
 3: for $k \leftarrow 0$ to $11$ do
 4:     if $GBR[k + temp][2] == QoSPDB$ then
 5:         if $GBR[k + temp][3] \geq app[i].PER$ then
 6:             $QoS[i].identifier \leftarrow GBR[k + temp][0]$
 7:             $break;$
 8:         end if
 9:     else
10:         $QoS[i].identifier \leftarrow 400$
11:     end if
12: end for
end
```

Lastly, for QoS flows of Non-GBR resource type we use the standardized values from Table 7.4. The pseudocode presented in Algorithm 6 uses the PER to map to Non-GBR QFIs, using column 3 in Table 7.4. Non-GBR QFIs can assure only flows with PER less than or equal to $10^{(-6)}$.

As the majority of QFIs assure a PER up to the power of (-6), our algorithm uniformly assigns traffic flows to different QFIs without overusing only one flow. To do so, the QoS-MAN algorithm reserves QFI 79 and QFI 7 to flows with PERs $10^0$ and $10^{-1}$ respectively, as shown on lines 2-6 of Algorithm 6, otherwise the algorithm selects between other QFIs. We use the temp variable to make sure the algorithm does not select the same QFI for every flow.

If there is no QFI that assures the requested PER, then the application is assigned to a non-significant QFI saying that the algorithm failed to fulfill the application's PER using the Non-GBR flows.

**Table 7.4:** QFIs for standardized Non-GBR flows.

| QoS/ QFI | Priority | Packet Error Rate (PER) |
|---|---|---|
| 69 | 5 | $10^{-6}$ |
| 5 | 10 | $10^{-6}$ |
| 70 | 55 | $10^{-6}$ |
| 6 | 60 | $10^{-6}$ |
| 79 | 65 | $10^{-2}$ |
| 80 | 68 | $10^{-6}$ |
| 7 | 70 | $10^{-3}$ |
| 8 | 80 | $10^{-6}$ |
| 9 | 90 | $10^{-6}$ |

## 7.4 Evaluation and Results

In this section, we present our experimental setup showing the performance of QoS-MAN on a set of evaluation scenarios.

### 7.4.1 Experimental setup

We consider 1000 applications with different QoS constraints on Deadline, Jitter, Bandwidth and Packet Error Rate. It is common for real-time systems to have tasks operating in different time bands [21]. The usual time bands for real-time systems are 1 ms-10 ms, 10 ms-100 ms, 100 ms-1 s [22]. For example, a temperature sensor will likely sample at a lower rate compared to a rotation speed sensor [23]. Considering the examples above, in our scenarios we consider real-time systems with tasks operating in a time band of 100 ms-1 s. We also randomly select the deadlines within the range of [100 ms-1 s]. The random selection of deadlines follows uniform distribution.

Jitter constraints are defined by random boolean values as we use them only in the first phase of the mapping algorithm, following the logic-based equations in Section 7.3. In addition, the bandwidth constraints are set to uniformly-distributed values in the range of [0%-100%]. 100% is the maximum guaranteed bandwidth of $\approx$ 2.16 Mbit/s as shown in Table 7.2. Zero is used as a boolean value to specify no bandwidth constraint.

We use packet error rates (PERs) to evaluate the performance of our algorithm. To get different ranges for PERs, we consider values from previous works (i) Packet Error Rates for in-body communication [24], and (ii) Packet Error Rates for a Mobile Wireless Access System [25] as shown in Table 7.5.

**Algorithm 6** *MappingToNonGBR(i)*

```
begin
  $i \leftarrow applicationID$
  if $app[i].PER == 0$ then
      $QoS[i].identifier \leftarrow Non\_GBR[4][0]$
  end if
  if $app[i].PER == 1$ then
      $QoS[i].identifier \leftarrow Non\_GBR[6][0]$
  end if
  if $app[i].PER > 1$ then
      for $k \leftarrow 0$ to $8$ do
          if $app[i].PER \leq Non\_GBR[k + temp][2]$ then
              $QoS[i].identifier \leftarrow Non\_GBR[k + temp][0]$
              $temp + +;$
              if $Non\_GBR[k + temp][2] == 2 || Non\_GBR[k + temp][2] == 3$ then
                  $temp + +;$
              end if
              if $temp > 8$ then
                  $temp = 0;$
              end if
              $break;$
          end if
      end for
  else
      $QoS[i].identifier = 0$
  end if
end
```

We also evaluate QoS-MAN algorithm for PER values in the range of predefined possible PER from 3GPP specifications.

### 7.4.2 Analysis of mapping results for different ranges of PER

We use three different scenarios to evaluate the performance of the QoS-MAN algorithm. The input to the algorithm is selected from different ranges of PER. In the first scenario, the application's constraints on PER are set to uniformly-distributed values in the range of $[10^{-12} - 10^{0}]$. Whereas, in the second and third scenarios, the PER values are set in the range of $[10^{-5} - 10^{0}]$ and $[10^{-8} - 10^{0}]$, respectively, as shown in Table 7.5. The main idea in this evaluation is to show the sensitivity of the proposed algorithm with respect to different PER inputs.

The results of QoS-MAN for scenario 1 are presented in Fig. 7.4. It is obvious that 5G QoS resource types of GBR and Non-GBR failed to fulfill some of the applications' constraints when the PER is set in the range of $[10^{-12} - 10^{0}]$.

**Table 7.5:** PER variations used to evaluate the QoS-MAN algorithm.

| **Evaluation Scenarios** | **PER (ranges)** |
|---|---|
| PERs for in-body communication [24] | $[10^{-12} - 10^{0}]$ |
| PERs for a Mobile Wireless System [25] | $[10^{-5} - 10^{0}]$ |
| Possible PERs for predefined QFIs in 5G [10] | $[10^{-8} - 10^{0}]$ |

This result was expected since predefined 5G QoS flows support PERs down to the level of $10^{-8}$. Any PER value less than $10^{-8}$ cannot be guaranteed by the predefined QFIs of the 5G system. The DC-GBR flows are not affected by PER constraints since the QoS-MAN algorithm selects the DC-GBR QFIs only on the basis of the Bandwidth constraint of the application.

We conclude that in scenario 1 the QoS-MAN algorithm can fulfill only 79.3% (shown in Fig. 7.7) of the applications' constraints since we are mapping the traffic flows to the predefined QFIs supporting PERs down to the level of $10^{-8}$.

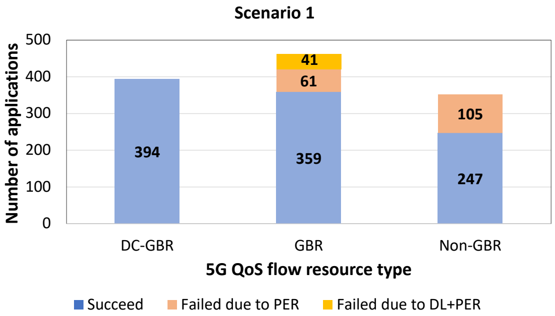


**Figure 7.4:** Number of applications that are either successfully assigned to each resource type QFIs or have failed to have their constraints fulfilled when PER $\in [10^{-12} - 10^{0}]$.

The results of QoS-MAN for scenario 2 are presented in Fig. 7.5. We run the algorithm with the same number of applications, but changing PER in ranges of $[10^{-5} - 10^{0}]$. The performance of the algorithm is significantly improved fulfilling 98.5% (shown in Fig. 7.7) of the applications' constraints as predefined QFIs of all resource types can guarantee PERs in the ranges of $[10^{-5} - 10^{0}]$. When it comes to GBR type of resources, our algorithm checks both DL and PER of the applications, and it might fail to assign it to a QFI which can fulfill the DL constraint but not the PER constraint and vice versa. For example in the case of a traffic flow with a deadline value of 100ms and a

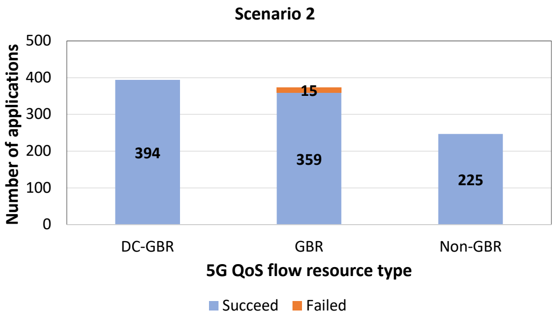


**Figure 7.5:** Number of applications that are either successfully assigned to each resource type QFIs or have failed to have their constraints fulfilled when PER $\in [10^{-5} - 10^{0}]$.

PER of $10^{-6}$, there is a set of predefined QFI(33, 65, 67, 1, 66) in Table 7.3 that can guarantee the deadline value of 100 ms but not the PER value of $10^{-6}$.

If we consider PERs in the ranges of predefined QoS characteristics in 5G, the QoS-MAN algorithm fulfills 89.7% (shown in Fig. 7.7) of the applications' constraints, failing 63 applications' constraints in PER from Non-GBR QoS flows (which can only guarantee PER down to the level of $10^{-6}$ in Table 7.4), and 40 applications' constraints in DL and PER from GBR QoS flows as shown in Fig. 7.6.

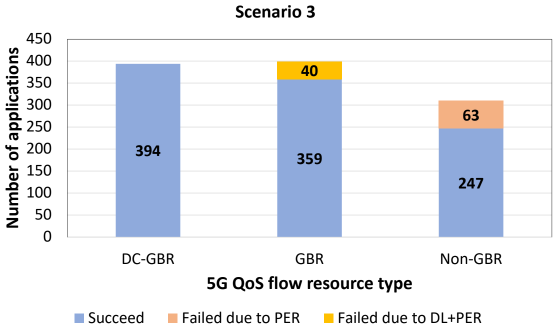


**Figure 7.6:** Number of applications that are either successfully assigned to each resource type QFIs or have failed to have their constraints fulfilled when PER $\in [10^{-8} - 10^{0}]$.

### 7.4.3 Analysis of traffic flows assigned to each QFI

To further evaluate the performance of the QoS-MAN algorithm, we investigate how the traffic flows are spread among the QFIs. In 5G, all traffic flows with the same QFI are entered to the same QoS flow. In this case, if all traffic

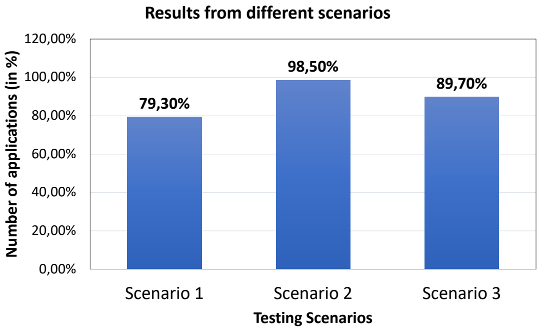


**Figure 7.7:** The percentage of applications whose constraints are fulfilled by QoS-MAN in each scenario.

flows are assigned to the same QFI then an overhead would be added to the transmission of these flows.

In Figs. 7.8, 7.9, and 7.10, we show how the traffic flows from different applications are mapped to predefined QFIs in a 5G system. There are only 5 possible QFIs for DC-GBR resources, which offer guarantees on very different bandwidth values. In this case, our algorithm is restricted as it depends on the Bandwidth constraint of the application, which in our case is uniformly distributed between values from 1%-90%. QFI 18 serves the majority of traffic flows as it is the only QFI that can guarantee bandwidth constraints over 50% of the maximum 2.16664 Mbit/s, while the remaining 4 QFIs serve the traffic flows with bandwidth constraints less then 50%.

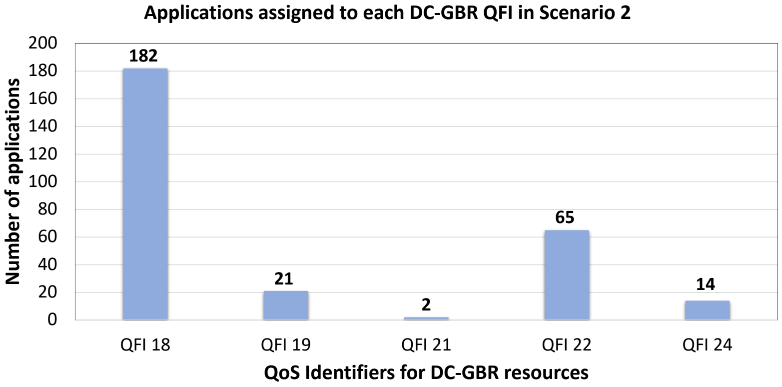


**Figure 7.8:** Number of applications assigned to each DC-GBR QFI when PER $\in [10^{-12} - 10^{0}]$.

Similarly, there are 12 possible QFIs for GBR resources. In this case, the QoS-MAN algorithm performs the mapping by selecting the QFI which fulfills the Deadline and PER constraints of the application. The traffic flows are spread among the QFIs, by first choosing the closest lower value to their deadline constraint and PER constraint. As shown in Fig. 7.9, QFI 74 is mostly used for the traffic flows. This QFI offers the highest PDB value of 500ms and lowest PER of $10^{-8}$. From the user deadline constraints, we claim that the QFI with a PDB of 500ms will serve all the traffic flows with a deadline constraint in the range of [500 ms-1000 ms]. Since the QFI 74 offers the lowest PER of $10^{-8}$, it ends up being mostly used by the mapping algorithm. A traffic flow which does not have a deadline constraint but has a jitter constraint is added to QFI 3 and 65 of GBR, selecting the one that provides guarantees in the requested PER.

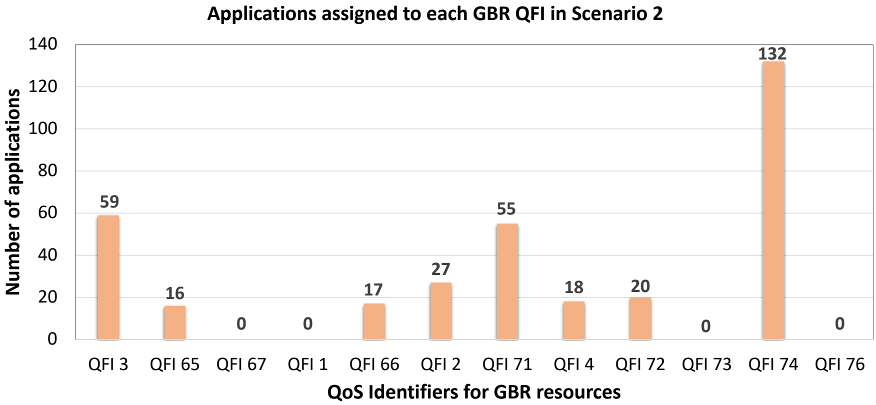


**Figure 7.9:** Number of applications assigned to each GBR QFI when PER $\in [10^{-12} - 10^{0}]$.

The effect of spreading the traffic flows among different QFIs can be clearly observed in Non-GBR resources as most of the QFIs of Non-GBR type guarantee the same PER of $10^{-6}$, while QFI 79 and QFI 7 guarantee PER of $10^{-2}$ and $10^{-3}$, respectively. Fig. 7.10 shows the proposed algorithm does not overuse one QFI, but it indeed spreads the flows between different QFIs to reduce the overhead inside the 5G QoS flows.

## 7.5 Conclusions and Future Work

In this paper, we advocated that one of the essential but challenging tasks in integrating Time Sensitive Networking (TSN) and 5G networks into a unified heterogeneous network is to map their QoS requirements. Therefore, we proposed a novel mapping algorithm to efficiently map TSN QoS requirements into 5G QoS characteristics. The proposed algorithm, called the QoS-MAN, can systematically and efficiently map any Ethernet traffic flows to 5G QoS

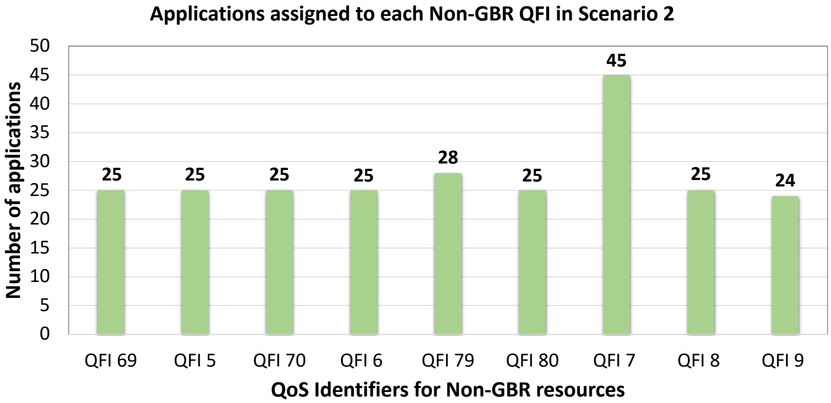


**Figure 7.10:** Number of applications assigned to each Non-GBR QFI when PER $\in [10^{-12} - 10^{0}]$.

flows. We evaluated the proposed algorithm using several synthetic scenarios with random sets of constraints on applications, including deadline, jitter, bandwidth and packet loss rate. The evaluation results show that the proposed mapping algorithm can effectively fulfill over 90% of the applications' constraints.

The proposed algorithm considers only the predefined QoS flow identifiers provided by the 3GPP specification, while there is also the opportunity to create new QoS flows with other identifiers. This can improve the performance of our mapping algorithm by achieving a fulfillment of 100% applications' constraints. Moreover, 5G defines a limitation of maximum 64 QoS flows in a PDU Session, which our mapping algorithm does not take in consideration. The future work entails to address this limitation of QoS flows in the QoS-MAN algorithm, while proposing a scheduling technique for TSN-5G network.

## Acknowledgment

This work is supported by the Swedish Governmental Agency for Innovation Systems (VINNOVA) via the PROVIDENT project and by the Swedish Knowledge Foundation via the projects DPAC & HERO. We thank all our industrial partners, especially Arcticus Systems & HIAB.

# Bibliography

[1] Lisa Underberg, Rüdiger Kays, Steven Dietrich, and Gerhard Fohler. Towards hybrid wired-wireless networks in industrial applications. In *2018 IEEE Industrial Cyber-Physical Systems (ICPS)*, pages 768–773, 2018.

[2] Hsin-Yeh Chen and Chia-han Lee. Analysis of the number of hops in wired-wireless heterogeneous networks. In *2012 IEEE Wireless Communications and Networking Conference (WCNC)*, pages 1806–1810, 2012.

[3] Alaa Al-Shaikhli, Amir Esmailpour, and Nidal Nasser. Quality of service interworking over heterogeneous networks in 5G. In *2016 IEEE International Conference on Communications (ICC)*, pages 1–6, 2016.

[4] Farnaz Farid, Seyed Shahrestani, and Chun Ruan. QOS Evaluation of Heterogeneous Networks: Application-Based Approach. *International Journal of Computer Networks and Communications (IJCNC)*, 8(1), 2016.

[5] Anqi Zhu, Songtao Guo, Bei Liu, Mingfang Ma, Jing Yao, and Xin Su. Adaptive multiservice heterogeneous network selection scheme in mobile edge computing. *IEEE Internet of Things Journal*, 6(4):6862–6875, 2019.

[6] Farnaz Farid, Seyed Shahrestani, and Chun Ruan. A Dynamic Model for Quality of Service Evaluation of Heterogeneous Networks. *International Journal of Wireless Networks and Broadband Technologies*, 9(2):17–42, 2020.

[7] Lucia Lo Bello, Riccardo Mariani, Saad Mubeen, and Sergio Saponara. Recent Advances and Trends in On-Board Embedded and Networked Automotive Systems. *IEEE Transactions on Industrial Informatics*, 15(2):1038–1051, 2019.

[8] Mohammad Ashjaei, Lucia Lo Bello, Masoud Daneshtalab, Gaetano Patti, Sergio Saponara, and Saad Mubeen. Time-Sensitive Networking in automotive embedded systems: State of the art and research opportunities. *Journal of Systems Architecture*, 117:102137, 2021.

[9] Almudena Díaz Zayas, Delia Rico, Bruno García, and Pedro Merino. A Coordination Framework for Experimentation in 5G Testbeds: URLLC as Use Case. In *Proceedings of the 17th ACM International Symposium on Mobility Management and Wireless Access*, MobiWac '19, page

71–79, New York, NY, USA, 2019. Association for Computing Machinery.

[10] Technical Specification Group Services and System Aspects; System architecture for the 5G system (5GS)(Release 16). Technical report, 3GPP TS 23.501, 10 2020.

[11] Dongmyoung Kim Junseok Kim and Sunghyun Choi. 3GPP SA2 architecture and functions for 5G mobile communication system. In *ICT Express*, volume 3, pages 1–8. Elsevier, 2017.

[12] Mykola Beshley, Natalia Kryvinska, Marian Seliuchenko, Halyna Beshley, Elhadi M. Shakshuki, and Ansar-Ul-Haque Yasar. End-to-End QoS “Smart Queue” Management Algorithms and Traffic Prioritization Mechanisms for Narrow-Band Internet of Things Services in 4G/5G Networks. *Sensors*, 20(8), 2020.

[13] TS 123 501: 5G; System architecture for the 5G System (5GS). Technical report, ETSI TS 123 501, 10 2020.

[14] Fernando Rodini. QoS/QoE developments in 4G-IoT & 5G technologies. *ITU Workshop on Telecommunications Service Quality*, pages 27–29, 2017.

[15] IEEE Standard for Local and metropolitan area networks – Bridges and Bridged Networks - Amendment 25: Enhancements for Scheduled Traffic. Technical report, IEEE Std 802.1Qbv-2015, 2016.

[16] Luxi Zhao, Paul Pop, Zhong Zheng, and Qiao Li. Timing Analysis of AVB Traffic in TSN Networks Using Network Calculus. In *2018 IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS)*, pages 25–36, 2018.

[17] Zenepe Satka, David Pantzar, Alexander Magnusson, Mohammad Ashjaei, Hossein Fotouhi, Mikael Sjödin, Masoud Daneshtalab, and Saad Mubeen. Developing a Translation Technique for Converged TSN-5G Communication. In *2022 IEEE 18th International Conference on Factory Communication Systems (WFCS)*, pages 1–8, 2022.

[18] Hong Zhang, Chuang Huang, Jing Zhou, and Liao Chen. QoS-Aware Virtualization Resource Management Mechanism in 5G Backhaul Heterogeneous Networks. *IEEE Access*, 8:19479–19489, 2020.

[19] Yajing Zhang, Qimin Xu, Mingyan Li, Cailian Chen, and Xinping Guan. QoS-Aware Mapping and Scheduling for Virtual Network Functions in Industrial 5G-TSN Network. In *2021 IEEE Global Communications Conference (GLOBECOM)*, pages 1–6, 2021.

[20] MiJeong Yang, SoonYong Lim, Sung-Min Oh, and Jaesheung Shin. An Uplink Transmission Scheme for TSN Service in 5G Industrial IoT. In *2020 International Conference on Information and Communication Technology Convergence (ICTC)*, pages 902–904, 2020.

[21] Alan Burns and Gordon Baxter. Time bands in systems structure. In *Structure for Dependability: Computer-Based Systems from an Interdisciplinary Perspective*, pages 74–88, London, 2006. Springer.

[22] P. Emberson, R. Stafford, and R.I. Davis. Techniques for the synthesis of multiprocessor tasksets. In *1st International Workshop on Analysis Tools and Methodologies for Embedded and Real-time Systems (WATERS)*, pages 6–11, July 2010.

[23] Jane W. S. Liu. *Real-Time Systems*. Prentice Hall, 2000.

[24] Maham Waheed, Rizwan Ahmad, Waqas Ahmed, Micheal Drieberg, and Muhammad Mahtab Alam. Towards efficient wireless body area network using two-way relay cooperation. *Sensors*, 18(2), 2018.

[25] Lai King Tee. Packet error rate and latency requirements for a mobile wireless access system in an ip network. In *2007 IEEE 66th Vehicular Technology Conference*, pages 249–253, 2007.

# Chapter 8

# Paper D: Work in progress - A centralized configuration model for TSN-5G networks

Zenepe Satka, Inés Álvarez, Mohammad Ashjaei, Saad Mubeen.
In the $27^{th}$ IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), 2022.

## Abstract

The integration of Time-Sensitive Networks (TSN) with 5G cellular networks requires a defined architecture for network configuration and management. Although 3GPP specifications provide necessary means for the TSN-5G integration, the operation of such converged TSN-5G network remains an open challenge for the research community. To address this challenge, this paper presents the ongoing work in developing a centralized architectural model to configure the TSN-5G network, and forward traffic from TSN to 5G and vice-versa. The proposed architectural model uses knowledge of the traffic characteristics to carry out a more accurate mapping of quality of service attributes between TSN and 5G.

## 8.1 Introduction

The advancement in the Industrial Internet of Things (IIoT) brings many advantages such as increase in productivity and safety in the industrial domains, decrease in the cost of infrastructure and production error rates, among others [1]. The IIoT employs numerous embedded IoT devices to increase automation, predict machine failures, monitor various components of the system, and ensure safe human-machine interaction [2]. These embedded IoT devices are often required to continuously communicate with each other as well as with the existing industrial infrastructure. In the case of timing predictable IIoT applications, the embedded devices require high-bandwidth, low-latency and timing predictable communication.

Ethernet is a promising communication technology to support high bandwidth wired communication. However, traditional Ethernet is unable to support low-latency and predictable communication. The IEEE 802.1 Time-Sensitive Networking (TSN) Task Group developed a set of standards for Ethernet to support the low-latency required by IIoT systems. Specifically, TSN standards provide low-latency, fault tolerance and online configuration capabilities to switched Ethernet communications[1]. For these reasons, TSN has become the most promising solution to build the communication infrastructures of novel industrial applications [3].

Another promising solution to meet the stringent low-latency communication of the industrial applications is the fifth generation of mobile network technology, i.e. 5G. This technology is capable of supporting the required levels of network latency with its Ultra-Reliable Low-Latency Communication (URLLC) service [4]. Furthermore, the Release 16 of 3rd generation partnership project (3GPP) [5] introduces the integration of TSN and 5G to ensure seamless operation of industrial automation devices. A converged TSN-5G network introduces a greater level of flexibility in the network communication, while meeting the requirements of high-bandwidth and low-latency communication.

Although 3GPP specifications provide the necessary means for the TSN-5G integration, the operation of such converged TSN-5G network in low-latency applications remains an open topic to the research community. Specifically, one of the key mechanisms to provide timing guarantees in TSN-5G networks is the mapping of TSN traffic to 5G. Currently, 3GPP proposes to map TSN traffic to 5G using priorities only. Nonetheless, this is not the most suitable approach to provide low-latency and bounded jitter. Instead, we propose to use a mapping technique that takes into account further traffic informa-

---

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

tion, i.e. the bandwidth, packet loss rate, deadline and maximum acceptable jitter [6].

Currently, the 3GPP specification proposes to carry out the mapping of TSN traffic to 5G within the 5G devices. Nonetheless, if we want to take advantage of the benefits provided by a richer mapping approach we can no longer carry out the mapping within the devices. On the one hand, the mapping would be more complex and, thus, harder to carry out on-the-fly every time a TSN frame is received. On the other hand, providing the necessary information about the traffic to each 5G device would introduce additional overhead in the network.

For these reasons, in this work we propose to carry out the traffic mapping within the Centralized Network Configuration entity (CNC) devised in the IEEE Std 802.1Qcc [7] standard. The CNC is responsible for configuring the network devices in TSN. We propose to take advantage of its complete view of the network and its knowledge of the traffic to carry out the mapping of TSN-5G traffic. Once the mapping is carried out, the CNC will use the Network Configuration (NETCONF) protocol to configure both TSN and 5G bridges.

The remainder of the paper is structured as follows. Section 8.2 provides an overview of the most important TSN and 5G concepts, as well as the existing related work. Section 8.3 describes the design rationale of the proposed configuration architecture. Finally, Section 8.4 concludes the paper by summarizing the most important contributions and pointing at future work directions.

## 8.2 Background and Related Work

In this Section we discuss the basic TSN and 5G concepts necessary to understand the rest of the paper, as well as the related work.

### 8.2.1 Background

#### Time Sensitive Networking

TSN is a set of standards developed by the TSN Task Group to provide standard Ethernet with low-latency, fault tolerance and online configuration capabilities. Specifically, the IEEE Std 802.1Qcc [7] standard proposes centralized architectures to support the online configuration of TSN networks. Centralized architectures are proven to be more adequate to carry out complex configuration decisions in real-time [8]. For this reason, there is a growing interest in using TSN's centralized architectures to configure the networks of IIoT applications, which are expected to be large and mutable.

The IEEE Std 802.1Qcc standard introduces two centralized architectures, namely the Centralized Network/Distributed User, in which only the network is managed by a centralized entity while the application is managed in a distributed manner; and the Fully Centralized architecture, where all the devices in the system are managed centrally. Figure 8.1 depicts the Fully Centralized architecture, which we selected to build our configuration architecture for TSN-5G networks.

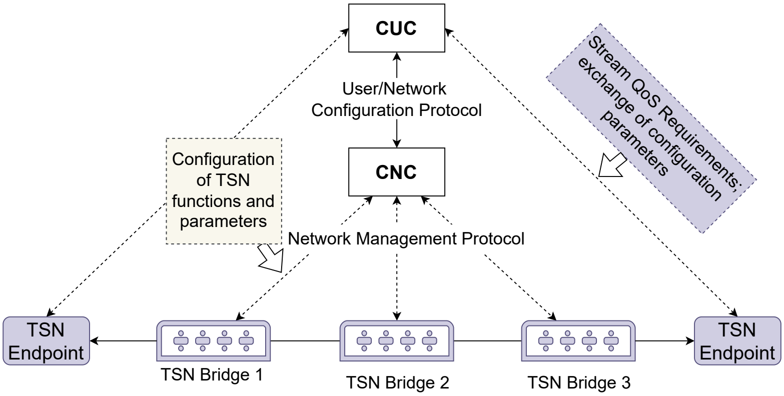


**Figure 8.1:** Fully Centralized TSN Configuration Model.

The Figure depicts a TSN network with 3 bridges, 2 end stations, the so-called Centralized User Configuration entity (CUC) and Centralized Network Configuration entity (CNC). On the one hand, the CUC is responsible for gathering the application requirements, calculating new possible configurations and informing the CNC about how these requirements affect the network, e.g. creation of a new stream of information or elimination of existing ones. On the other hand, the CNC is responsible for monitoring the network, calculating new network configurations based on the information received from the CUC or the network itself, and deploying the configuration in the bridges.

The flow of information of this model is as follows:

- The end stations send their Quality of Service (QoS) requirements to the CUC entity, such as data rate, traffic class, priorities and worst-case latency.
- The CUC relays the end stations' requirements to the CNC entity.
- The TSN bridges send their capabilities to the CNC. These capabilities

include bridge delays per port and class, propagation delays per port, and priorities.

- Since the CNC has an overview of the whole network, it calculates an adequate configuration for the network. This configuration may include the schedule of the time-triggered traffic, but also the configuration of mechanisms for the timely transmission of event-triggered traffic or for frame preemption.

#### 5G network

The fifth generation of mobile networks (5G) is designed to address six challenges that were not adequately addressed by the previous generations of mobile networks i.e. higher capacity, higher data rate, lower end to end latency, massive device connectivity, reduced cost and consistent Quality of Experience provisioning [9, 10].

The 3rd Generation Partnership Project (3GPP)[2] identifies Ultra-Reliable Low-Latency Communication (URLLC) as a key usage scenario of 5G. URLLC is applied for the event notification of critical applications with low-latency and reliability requirements, such as vehicular and industrial control applications [11]. The capabilities of URLLC makes 5G a suitable wireless candidate for time-sensitive communication achieving ultra-low latency down to 1 ms and reliability up to 99.9999% [12]. 5G key URLLC capabilities enable the integration of 5G mobile network with TSN wireline network providing converged deterministic connectivity for industrial automation.

### 8.2.2 Related Work

There are several existing works focusing on the integration model of TSN-5G network. In this section, we present an overview of the works that have been proposed in the literature.

Ginthör et al. [13] present a joint configuration approach that enables end to end scheduling optimization over a bridged TSN-5G network. The architectural model of the network consists of a converged network with several TSN bridges and 5G as a logical TSN bridge. The authors use the fully centralized network configuration model, which is suitable for end to end optimized schedules. Similarly, authors in [14–16] analyze the integration of TSN-5G considering 5G as a logical TSN bridge, while utilizing the centralized network configuration model. Such integration consists of 3 TSN translators (TT)

---

[2] https://www.3gpp.org/about-3gpp

used as an interface with a TSN network while achieving transparency of 5G system: (i) Device-side TSN translator (DS-TT) located at the User Equipment (UE), (ii) Network-side TSN translator (NW-TT) residing at the User Plane Function (UPF), and (iii) TSN Application Function (TSN AF) which is responsible for showing the 5G system capabilities to the CNC and then carries out the mapping of TSN traffic to 5G and manages the traffic forwarding.

In our work, we move the mapping functionality from the TSN AF to the CNC, as the CNC has the information needed to map TSN QoS requirements to 5G QoS profiles using more advanced mapping techniques [6]. To the best of our knowledge, this is the first proposed architecture that maps TSN traffic to 5G QoS profiles in a TSN CNC.

## 8.3 Proposed Architecture

A converged TSN-5G architecture requires translation functionalities to forward the traffic and different QoS-es from the wired to the wireless network and vice-versa. The 3GPP Release 16 [5] standardizes these translation functionalities into 3 parts: 1) DS-TT function, which resides on a UE side of 5G network, 2) NW-TT function, which resides in the UPF side (both on the user plane), and 3) 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 QoS Identifiers or profiles specified in 3GPP Release 16 [5].

As we have discussed in Section 8.1, the current 3GPP integration of 5G and TSN proposes to carry out the mapping of TSN traffic to 5G within the 5G systems. Furthermore, the mapping consists in a correspondence between TSN priorities and 5G QoS Identifiers. Unfortunately, this mapping technique does not allow to take advantage of the wide range of QoS Identifiers available in 5G. For this reason, we use a QoS mapping technique between TSN and 5G not only based on traffic classes of a TSN network, but using other QoS parameters such as deadline, jitter, bandwidth, and packet loss rate which allows to provide a higher granularity of the QoS.

In order to take advantage of the benefits brought by our mapping function we need to modify the configuration architecture. Specifically, we move the TSN AF functionality inside the CNC for a series of reasons. First, the CNC has the complete view of the network, which means it already has all the information required to perform the QoS mapping between TSN and 5G traffic. Second, since this mapping technique is more complex, it requires higher computation resources than those available in 5G systems. Third, performing the mapping in the CNC allows to perform it only once for the entire network, instead of having to execute it once in each 5G system. Finally, carrying the mapping out in the CNC prevents introducing additional bandwidth and timing overhead in the network, as the only information that must be transmitted is the result of the mapping, and not the entire traffic information. Figure 8.2 depicts the proposed architecture, which we will explain in detail next.

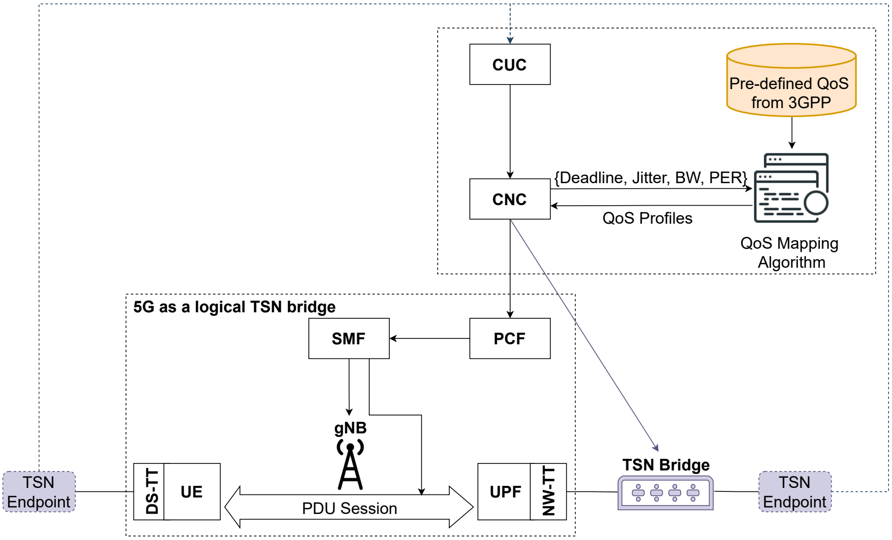


**Figure 8.2:** The centralized configuration model of a TSN-5G network.

### 8.3.1 5G QoS Characteristics

3GPP Release 16 [5] provides predefined QoS profiles based on the type of service that is used. The QoS profiles are represented by a 5G QoS Identifier (5QI), which is a reference to a set of predefined QoS characteristics. The set of QoS characteristics includes:

- Resource type - The QoS flows can be Guaranteed Bit Rate (GBR), Delay-critical Guaranteed Bit Rate (DC-GBR), or Non-Guaranteed Bit Rate (Non-GBR). In case of GBR flows, 5G pre-allocates dedicated resources in a radio base station.

- Default priority level - Each QoS flow has its own priority level, used to prioritize between different flows of a UPF.

- Packet Delay Budget (PDB) - It defines an upper bound of the time a packet can spend within 5G system without being dropped.

- Packet Error Rate (PER) - Similarly to packet loss rate, in 5G PER defines the number of packets that could not be successfully delivered to the corresponding receiver.
- Default Maximum Data Burst Volume (MDBV) - 5G defines the largest amount of data that can be transmitted by the radio unit within the PDB period.
- Default Average Window - It indicates the duration of time to calculate two QoS parameters of a 5G network: (i) the Guaranteed Flow Bit Rate (GFBR), and (ii) Maximum Flow Bit Rate (MFBR).

This set of predefined 5G QoS characteristics is saved in the knowledge database of pre-defined QoS from 3GPP, presented in Figure 8.2.

### 8.3.2 QoS Mapping Algorithm

A QoS mapping algorithm [6] is introduced to map the TSN QoS requirements to the predefined 5G QoS characteristics represented by the 5QI. This algorithm takes two inputs:

1. The predefined QoS characteristics from 3GPP Release 16, which are saved in a knowledge database.
2. The set of TSN QoS-es i.e, Deadline, Jitter, Bandwidth (BW), and Packet Error Rate (PER).

The QoS Mapping algorithm compares the TSN QoS to the predefined 5G QoS-es and chooses the set of characteristics that fulfills the requested QoS based on specific functions presented in [6]. After performing all its calculations the algorithm sends to the CNC the 5G QoS Flow Identifier which will be used for further forward treatment of the flow inside the 5G system.

### 8.3.3 TSN-5G Sample Workflow

This section describes the sample workflow in the proposed TSN-5G architecture which includes TSN bridges and 5G as a logical TSN bridge. The workflow is as follows:

- **Step 1:** The CUC collects all the requirements of various applications in the network from the TSN endpoints and forwards them to the CNC.

- **Step 2:** The CNC has all the knowledge on the capabilities and boundaries of the bridges in the network in advance. It also has the traffic information of the entire network, which it can derive from the communication requirements received from the CUC. Based on network and traffic information, the CNC computes a schedule for the requested TSN flows.

- **Step 3:** In our architecture, if a TSN flow has a receiver connected through the 5G system, the CNC will have to perform another step, which consists of mapping the TSN QoS requirements to the 5G QoS Figure 8.2. After obtaining the specific 5G QoS Identifier, the CNC computes the schedule for the 5G system, and shares the 5G QoS Identifiers to the Policy Control Function (PCF) of each 5G system for further traffic forwarding treatment.

- **Step 4:** The CNC configures all the bridges, regardless of whether they are TSN or 5G, following the calculated configuration. To that, we propose to use NETCONF [17], a network configuration protocol that follows a client-server architecture. The CNC has a NETCONF client which triggers the configuration of all the network devices. Each device has a NETCONF server embedded which will read the information received from the CNC and will apply it. In order for the 5G systems to communicate with the CNC, we need to define a YANG data model that specifies which information the PCF will use to configure the QoS-es of the traffic. The definition of the YANG data model is left as future work.

## 8.4 Summary and Ongoing Work

TSN standards and 5G are promising technologies to build the networks of future IIoT systems, as both technologies are suitable for providing flexibility, high-bandwidth and low-latency to the communications. However adequate mechanisms must be put in place to support adequate forwarding of the traffic in TSN-5G networks. One key aspect is the mapping of TSN traffic to 5G QoS profiles to ensure that the timing guarantees of the traffic are met.

Currently, most works propose to use a simple mapping based on TSN's traffic priorities to 5G QoS profiles. However, this mapping cannot take full advantage of the 5G profiles, which can result in the loss of QoS. For this reason, we proposed to use a mapping technique that uses knowledge of the traffic characteristics to carry out a more accurate mapping. To support this mapping technique, we defined an adequate network architecture.

In this work, we proposed to use TSN's fully centralized architecture to carry out the mapping of TSN traffic to 5G. We discussed the main aspects of the architecture, i.e., which devices are involved and how they inter-operate. Furthermore, we proposed a workflow, which defines the different activities required to properly configure a TSN-5G network using the proposed architecture.

Currently, we are working on providing a YANG model that defines the different aspects to be configured in the 5G systems to adequately forward TSN traffic following the results of the proposed mapping. The result of this mapping approach will be the end to end scheduling algorithm for TSN-5G network. We plan to implement the entire approach in a well-known simulator named NeSTiNg, that is based on the OMNeT++ tool.

## Acknowledgement

The work in this paper is supported by the Swedish Governmental Agency for Innovation Systems (VINNOVA) through the DESTINE, PROVIDENT and INTERCONNECT projects and KKS foundation through the projects DPAC, HERO and FIESTA. The authors would like to thank all industrial partners, especially Arcticus Systems, HIAB and Volvo Construction Equipment, Sweden.

# Bibliography

[1] Vehbi C. Gungor and Gerhard P. Hancke. Industrial wireless sensor networks: Challenges, design principles, and technical approaches. *IEEE Transactions on Industrial Electronics*, 56(10):4258–4265, 2009.

[2] Jens Hiller, Martin Henze, Martin Serror, Eric Wagner, Jan Niklas Richter, and Klaus Wehrle. Secure low latency communication for constrained industrial iot scenarios. In *2018 IEEE 43rd Conference on Local Computer Networks (LCN)*, pages 614–622, 2018.

[3] Mohammad Ashjaei, Lucia Lo Bello, Masoud Daneshtalab, Gaetano Patti, Sergio Saponara, and Saad Mubeen. Time-Sensitive Networking in automotive embedded systems: State of the art and research opportunities. *Journal of Systems Architecture*, 117:102137, 2021.

[4] Almudena Díaz Zayas, Delia Rico, Bruno García, and Pedro Merino. A Coordination Framework for Experimentation in 5G Testbeds: URLLC as Use Case. In *Proceedings of the 17th ACM International Symposium on Mobility Management and Wireless Access*, MobiWac '19, page 71–79, New York, NY, USA, 2019. Association for Computing Machinery.

[5] Technical Specification Group Services and System Aspects; Study on enhancement of 5G System (5GS) for vertical and Local Area Network (LAN) services (Release 16). Technical report, 3GPP TR 23.734, 06 2019.

[6] Zenepe Satka, Mohammad Ashjaei, Hossein Fotouhi, Masoud Daneshtalab, Mikael Sjödin, and Saad Mubeen. QoS-MAN: A Novel QoS Mapping Algorithm for TSN-5G Flows. In *2022 IEEE 28th International Conference on Embedded and Real-Time Computing Systems and Applications (RTCSA)*, pages 220–227, 2022.

[7] IEEE Standard 802.1Qcc. IEEE Standard for Local and Metropolitan Area Networks–Bridges and Bridged Networks–Amendment 31: Stream Reservation Protocol (SRP) Enhancements and Performance Improvements, 10 2018.

[8] Inés Álvarez, Luís Moutinho, Paulo Pedreiras, Daniel Bujosa, Julián Proenza, and Luis Almeida. Comparing Admission Control Architectures for Real-Time Ethernet. *IEEE Access*, 8:105521–105534, 2020.

[9] A. Gupta and R. K. Jha. A Survey of 5G Network: Architecture and Emerging Technologies. *IEEE Access*, 3:1206–1232, 2015.

[10] Patrick Kwadwo Agyapong, Mikio Iwamura, Dirk Staehle, Wolfgang Kiess, and Anass Benjebbour. Design considerations for a 5G network architecture. *IEEE Communications Magazine*, 52(11):65–75, 2014.

[11] Yu-Jia Chen, Li-Yu Cheng, and Li-Chun Wang. Prioritized resource reservation for reducing random access delay in 5G URLLC. In *2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, pages 1–5, 2017.

[12] Rashid Ali, Yousaf Bin Zikria, Ali Kashif Bashir, Sahil Garg, and Hyung Seok Kim. URLLC for 5G and Beyond: Requirements, Enabling Incumbent Technologies and Network Intelligence. *IEEE Access*, 9:67064–67095, 2021.

[13] David Ginthör, René Guillaume, Johannes von Hoyningen-Huene, Maximilian Schüngel, and Hans D. Schotten. End-to-end Optimized Joint Scheduling of Converged Wireless and Wired Time-Sensitive Networks. In *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, volume 1, pages 222–229, 2020.

[14] Ana Larrañaga, M. Carmen Lucas-Estañ, Imanol Martinez, Iñaki Val, and Javier Gozalvez. Analysis of 5G-TSN Integration to Support Industry 4.0. In *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, volume 1, pages 1111–1114, Vienna, Austria, 2020. IEEE.

[15] David Ginthör, Johannes von Hoyningen-Huene, Rene Guillaume, and Hans Schotten. Analysis of Multi-user Scheduling in a TSN-enabled 5G System for Industrial Applications. In *2019 IEEE International Conference on Industrial Internet (ICII)*, pages 190–199, 2019.

[16] Mahin K. Atiq, Raheeb Muzaffar, Oscar Seijo, Inaki Val, and Hans-Peter Bernhard. When IEEE 802.11 and 5G Meet Time-Sensitive Networking. *IEEE Open Journal of the Industrial Electronics Society*, 3:14–36, 2022.

[17] Rob Enns, Martin Björklund, Jürgen Schönwälder, and Andy Bierman. Network Configuration Protocol (NETCONF). *RFC 6241*, June 2011.