UNIVERSITAT POLITÈCNICA DE VALÈNCIA

Exploring the Future of Small Cells: Network Function Virtualization and Time Sensitive Networking

Departamento de Comunicaciones
Universitat Politècnica de València

A thesis submitted for the degree of
Doctor por la Universitat Politècnica de València
Valencia, May 2025

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To my parents,
to my sister and my brothers,
for all their support
along this journey.

To my beloved husband,
and to my two wonderful children,
who are my greatest source of strength and joy.

Abstract

The rapid expansion of 5G mobile communication networks introduces advanced network functionalities, including the critical integration of Small Cells (SC) and Network Function Virtualization (NFV) to address demands for low latency, high data capacity, and reliable connectivity. This thesis investigates the incorporation of Time-Sensitive Networking (TSN) into 5G SC architectures to facilitate reliable, real-time data synchronization essential for industrial applications. Through detailed analyses, it explores the potential of TSN-enabled small cells for precision synchronization, employing novel dual connectivity mechanisms, network slicing, and physical layer techniques to maintain accuracy.

Additionally, a Time-Locked Loop (TLL) and generalized Precision Time Protocol (gPTP) enable enhanced synchronization for automated environments, effectively addressing the unique requirements of Industrial Internet of Things (IoT) and Ultra-Reliable Low Latency Communication (URLLC) applications. The findings illustrate the enhanced synchronization capabilities of SCs through high-precision TSN translators positioned at the cell level, achieving synchronization tolerances as fine as ten nanoseconds, thus opening pathways for future deployments of small cells in Industry 4.0 and beyond.

The thesis deals with the problem of synchronization holistically, analyzing aspects of protocol design, architecture, and virtualization.

The developed architecture significantly optimizes network resources, reduces signaling complexity, and enhances 5G's capability to support critical industrial applications, setting a foundation for scalable, low-latency 6G networks.

Resumen

La rápida expansión de las redes de comunicación móvil 5G introduce funcionalidades avanzadas, incluyendo la integración crítica de celdas pequeñas (small cells - SC) y la virtualización de funciones de red (Network Function Virtualization - NFV) para satisfacer las demandas de baja latencia, alta capacidad de datos y conectividad fiable. Esta tesis investiga la incorporación de redes sensibles al tiempo (Time-Sensitive Networks - TSN) en arquitecturas de SC en 5G para facilitar la sincronización de datos en tiempo real y de alta fiabilidad, esencial para aplicaciones industriales. A través de análisis detallados, explora el potencial de las celdas pequeñas habilitadas para TSN para lograr una sincronización precisa, empleando mecanismos de doble conectividad novedosos, segmentación de red y técnicas a nivel de capa física para mantener la precisión.

Además, un bucle de bloqueo de tiempo (Time Locked Loop - TLL) y el protocolo de tiempo de precisión generalizado (generalized Precision Time Protocol - gPTP) permiten una sincronización mejorada para entornos automatizados, abordando eficazmente los requisitos únicos de aplicaciones industriales IoT y de comunicaciones ultraconfiables y de baja latencia (Ultra-Reliable Low Latency Communication - URLLC). Los hallazgos ilustran las capacidades mejoradas de sincronización de las SC a través de traductores TSN de alta precisión posicionados a nivel de celda, logrando tolerancias de sincronización de hasta diez nanosegundos, lo que abre el camino para futuras implementaciones de celdas pequeñas en la Industria 4.0 y más allá.

La tesis aborda el problema de la sincronización de manera holística, analizando aspectos de diseño de protocolos, arquitectura y virtualización.

La arquitectura desarrollada optimiza significativamente los recursos de red, reduce la complejidad de la señalización y mejora la capacidad del 5G para soportar aplicaciones industriales críticas, estableciendo una base para redes 6G escalables y de baja latencia.

Resum

L'expansió ràpida de les xarxes de comunicació mòbil 5G introdueix funcionalitats avançades, incloent-hi la integració crítica de les cel·les petites (small cell - SC) i la virtualització de funcions de xarxa (Network Function Virtualization - NFV) per a satisfer les demandes de baixa latència, alta capacitat de dades i connectivitat fiable. Aquesta tesi investiga la incorporació de la Xarxa Sensible al Temps (Time-Sensitive Network - TSN) en arquitectures de SC en 5G per a facilitar la sincronització de dades en temps real i d'alta fiabilitat, essencial per a aplicacions industrials. A través d'anàlisis detallades, s'explora el potencial de les cel·les petites habilitades per a TSN per a aconseguir una sincronització precisa, emprant mecanismes de doble connectivitat innovadors, segmentació de xarxa i tècniques a nivell de capa física per a mantindre la precisió.

A més, un bucle de bloqueig de temps (Time Locked Loop - TLL) i el protocol de temps de precisió generalitzat (generalized Precision Time Protocol - gPTP) permeten una sincronització millorada per a entorns automatitzats, abordant eficaçment els requisits únics de les aplicacions d'Internet de les Coses Industrial (Internet of Things - IoT) i de comunicacions ultraconfiables i de baixa latència (Ultra-Reliable Low Latency Communication - URLLC). Els resultats il·lustren les capacitats millorades de sincronització de les SC a través de traductors TSN d'alta precisió posicionats a nivell de cel·la, aconseguint toleràncies de sincronització de fins a deu nanosegons, obrint així camins per a futures implementacions de cel·les petites en la Indústria 4.0 i més enllà.

La tesi aborda el problema de la sincronització de manera holística, analitzant aspectes de disseny de protocols, arquitectura i virtualització.

L'arquitectura desenvolupada optimitza significativament els recursos de xarxa, redueix la complexitat de la senyalització i millora la capacitat del 5G per a donar suport a aplicacions industrials crítiques, establint una base per a xarxes 6G escalables i de baixa latència.

Acknowledgements

First of all, my deepest and most sincere thanks to my supervisor. I thank Prof. Narcís Cardona for guiding me and supporting me along this journey that began with many doubts and ended with the need to learn always more.

In the same way, a special thanks to all who believed in me. To my colleagues in Casa Systems, for the endless technical discussions. Now in Axyomcore, things are still soft because the team has no limits.

I thank Dr. David González Serrano and Dr. David Gutierrez Estéves for their work as reviewers of the Thesis. Special thanks also to Dra. Ruiz, Dr. Cano, and Dr. Garcia-Roger for acting as members of the committee.

Finally, I would like to express my deepest gratitude to those closest to me. My family, my beloved sons, Sofía and Adam, and my husband, for always being there.

Thank you all very much.

Faiza

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Acronyms

3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
5GS	5G System
6G	Sixth Generation
5GC	5G Core
DAS	Distributed Antenna Systems
5CN	5G Core Network
AI	Artificial Intelligence
AR	Augmented Reality
AMF	Access and Management Function
BBU	Base Band Unit
CNC	Central Network Controller
CUPS	the Control and User Plane Separation
CAG	Closed Access Group
CSI	Channel State Information
DHCP	Dynamic Host Configuration Protocol
DL	Down Link
DNS	Domain Name Service
DS-TT	Device Side TSN Translator
DC	Dual Connectivity
DL	Downlink
eMBB	Enhanced Mobile Broadband
	evolved NodeBs
eNB	evolved NodeB
EPC	Evolved Packet Network

Femto	Femtocell
GRE	Generic Routing Encapsulation
GM	Grandmaster
gPTP	Generalized Precision Time Protocol
GNSS	Global Navigation Satellite Systems
gNB	Next Generation Node B
HeNB	Home eNB
HgNB	Home gNB
HeNB-GW	Home eNB Gateway
HgNB-GW	Home gNB Gateway
IoT	Internet of Things
IaaS	Infrastructure-as-a-Service
IIoT	Industrial IoT
LTE	Long Term Evolution
MIMO	Multiple-Input Multiple-Output
mMTC	massive Machine Type Communications
mmW	Millimeter Wave
MEC	Mobile Edge Computing
ML	Machine Learning
MR-DC	Multi-RAT Dual Connectivity
MAC	Medium Access Control
MN	Master Node
MCG	Master Cell Group
MeNB	Master eNB
MgNB	Master gNB
mmWave	millimeter-wave
MTC	Machine Type Communication
NFV	Network Functions Virtualization
NR	New Radio
NW-TT	Network Side TSN Translator
NG-RAN	Next Generation Radio Access Network
NSSF	Network Slice Selection Function
NSA	Non Standalone
O-RAN	Open-RAN

OFDM	Orthogonal Frequency Division Multiplexing
gNB-DU	gNB Distributed Unit
gNB-CU	gNB Central Unit
GPS	Global Positioning System
PTP	Precision Time Protocol
PaaS	Platfrom as a Service
PCF	Policy Control Function
SC	Small Cell
SCF	Small Cell Forum
SA1	Service Architecture Working Group 1
SA	Standalone
SCG	Secondary Cell Group
SCS	Subcarrier Spacing
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RAT	Radio Access Technology
RRM	Radio Resource Management
RAT	Radio Access Technologies
RTI	Reference Time Information
RRC	Radio Resource Configuration
RRU	Remote Radio Unit
RLC	Radio Link Control
RF	Radio Frequency
PDCP	Packet Data Convergence Protocol
PDU	Packet Data Unit
RR	Rate Ratio
RB	Resource Block
SDN	Software-Defined Networking
SON	Self Organized Network
SIB9	System Information Block 9
SN	Secondary Node
SRB	Signalling Radio Bearer
SgNB	Source gNB

S-SN	Source SN
SLA	Service Level Agreement
SC-TT	Service Level Agreement
TDD	Time Division Duplexing
TS	Technical Specification
TSN	Time-Sensitive Networking
TSN AF	TSN Application Function
TESC	TSN-enabled Small Cell
THz	Terahertz
TRP	Transmission Reception Point
TSCTSF	Time-Sensitive Communication Time Synchronization Function
TR	Technical Report
T-SN	Target SN
TSi	Ingress Timestamp
TLV	Type Length Value
TSe	Egress Timestamp
TA	Timing Advance
TSC	Time Sensitive Communication
TLL	Time-Locked Loop
UE	User Equipment
UL	Up Link
URLLC	Ultra-Reliable and Low Latency Communications
UPF	User Plane Function
uMBB	ultra Mobile Broadband
UTC	Coordinated universal Time
UL	Uplink
V2X	Vehicle-to-anything
VLAN	Virtual Local Area Network
VR	Virtual Reality
VSC	Virtual Small Cell
vRAN	Virtual RAN
VM	Virtual Machine
VNF	Virtual Network Function

VPN	Virtual Private Network
VXLAN	Virtual eXtensible Local Area Network
XR	Augmented Reality

Chapter 1

Introduction

The first chapter of this thesis lays the foundational groundwork necessary for understanding the research focus and key themes explored throughout the study. This chapter establishes the intellectual context that underpins the investigation by presenting a comprehensive overview of motivation, historical developments, and current perspectives, grounded on the state-of-the-art. The objective is to highlight the importance of the research topic and clarify the scope of inquiry, situate the work within the broader academic discourse, and outline the key questions that drive subsequent analysis.

To that end, this chapter has been divided into the following sections:

- Section 1.1 examines the various use cases and factors propelling the diversification of Small Cell (SC) architectures in the 5G era, particularly emphasizing the necessity of SC for URLLC applications.

- Section 1.2 explores the current state of the field in this Thesis, highlighting the contributions of key telecommunications standards and frameworks such as Open-RAN (O-RAN), Third Generation Partnership Project (3GPP), and Small Cell Forum (SCF). The focus is on the latest advancements and emerging trends, specifically within SC and 5G networks.

- Section 1.3 identifies the main problem that motivates this Thesis and defines the research hypothesis.

- Section 1.4 defines the research objectives of this Thesis.

- Section 1.5 outlines the structure of the Thesis, summarizing the main contents of each chapter.

- Section 1.6 lists the publications related to this Thesis, including journals, conference papers, and patent.

1.1 Motivation

In this section, we provide the background and context that support the development of the thesis. We start with the evolution of SC technology and its associated product definitions, alongside examining scenarios where the utilization of SC is indispensable in 5G. We focus on the utilization of SC networks to support Ultra-Reliable and Low Latency Communications (URLLC) and Industrial Internet of Things (IoT).

1.1.1 SC for Enhancing 5G Connectivity and Paving the Way for 6G

With the rapid evolution of telecommunications technology, the demand for high-speed and reliable wireless communication has surged exponentially. This growth is primarily fueled by the increasing reliance on mobile devices and the rapid increase of data-intensive applications and services. Over the past few years, global mobile data consumption has experienced a significant uptick, with projections indicating a continued upward trajectory. Based on Ericsson Mobility Data and forecasts, the average mobile data usage per smartphone will increase from 21 GB in 2023 to 56 GB by 2029. Furthermore, 5G's portion of mobile data traffic is anticipated to surge to 76 percent by 2029, with total mobile data traffic expected to expand approximately threefold between 2023 and 2029 [1].

The advent of Fifth Generation (5G) networks marks a pivotal moment in the telecommunications landscape, offering high data speed, ultra-low latency, and enhanced network capacity. As 5G networks become more widespread, they are expected to play a transformative role in various sectors, including healthcare, manufacturing, transportation, and entertainment.

However, the transition to 5G networks presents several challenges, particularly regarding infrastructure deployment and network optimization. While effective in providing coverage over large areas, traditional macro base stations may struggle to meet the growing demand for data capacity in densely populated urban areas and indoor environments. This limitation has necessitated the adoption of alternative solutions, such as SC and Distributed Antenna Systems (DAS), to complement existing infrastructure and improve network performance.

SC, in particular, has emerged as a critical component of next-generation cellular networks. These compact base stations are designed to provide targeted coverage and capacity enhancements in areas with high data demand, such as urban centers, stadiums, shopping malls, and office buildings. By strategically deploying SCs, service providers can alleviate network congestion, improve indoor signal penetration, and deliver a seamless wireless experience to users across various environments.

In addition to addressing immediate capacity and coverage requirements, deploying SCs lays the groundwork for future network advancements, including

transitioning to the Sixth Generation (6G) technology. As telecommunications continue to evolve, SCs are expected to play an increasingly integral role in shaping the future of wireless communication, facilitating ubiquitous connectivity and unlocking new opportunities for innovation and economic growth.

1.1.2 Use Cases of SC

Small cells are vital in addressing the increasing demand for data capacity and coverage, particularly in areas where traditional macro base stations face limitations. Here are some key use cases for small cells:

- Urban Coverage Enhancement: SCs are deployed in densely populated urban areas, such as downtown districts, where traditional macrocell coverage may be insufficient due to high obstructions or population density. By installing SCs on light posts or buildings at street level, service providers can improve outdoor coverage and ensure reliable connectivity for users in crowded urban environments. For this scenario, we may use picocells with a power output of 0.25-1 watt and a 0.1-0.2 km radius.

- Indoor Coverage Enhancement: Indoor spaces like malls, stadiums, and train stations often experience poor signal penetration from macrocell towers, leading to user connectivity issues. With a low power output of 0.001-0.25 watts and a SC radius of 0.010-0.1 km, femtocells are ideal for improving indoor coverage in spaces like malls, stadiums, and train stations. They address the issue of poor signal penetration from macrocell towers and ensure reliable connectivity for indoor users.

- Enterprise Solutions: Microcells, with a 1-10 watts power output and a cell radius of 0.2-2.0 km, are suitable for industrial environments such as manufacturing sites. They provide dedicated wireless connectivity for critical industrial applications, ensuring high-quality service and supporting operations in challenging environments.

- Residential Connectivity: Residential SCs, like femtocells, are primarily designed for indoor coverage, they also serve as residential solutions. These plug-and-play devices are self-installed within households to improve in-home connectivity, offering residents reliable wireless connectivity and enhancing the overall user experience.

- Capacity Expansion: SCs alleviate network congestion by offloading traffic from macrocell towers in areas experiencing high data demand, such as stadiums or concert venues. By distributing capacity more efficiently, SCs ensure users can access high-speed data services even in densely populated areas with high data consumption. While not technically small cells, macrocells are used here as they represent traditional large-scale base stations. It has a power output from 10 to over 50 watts and a larger cell radius of 8-30 km.

Overall, SCs serve as versatile solutions for enhancing coverage, capacity, and connectivity in various environments, meeting the diverse needs of both consumers and businesses in the rapidly evolving telecommunications landscape.

1.1.3 SC as a Key Enabler for 5G

For 5G networks, the shift towards virtualized, disaggregated systems means that some SCs will be composed of two or three separate components. In contrast, others will remain as integrated units. The characteristics of 5G SC products—such as their size, power, interfaces, and specifications—will vary depending on the specific usage and deployment scenario. Based on the annual report published by SCF [2], three major trends are fueling a notable diversification in small cell form factors and architectures anticipated for 2025:

- Expanded range of use cases: Cellular technology is no longer limited to traditional mobile broadband services but is adopted by various enterprises, industries, and government agencies for diverse purposes. Different environments and use cases demand distinct performance and form factor requirements, ranging from large distributed radio systems for campuses to discreet units embedded in pavements for smart traffic applications. Additionally, various spectrum bands, including shared spectrum, will come into play.

- Network virtualization: The mobile network is transitioning towards disaggregated, multi-vendor architectures where radio units are separated from virtualized baseband units. This separation can occur in different configurations depending on the requirements of the specific use case.

- 5G roll-out: The deployment of 5G networks will further drive the proliferation of SC designs as it necessitates densification and scalability to new levels. 5G will often be deployed in relatively high-frequency bands, making SCs a suitable choice. It will also be designed as a pervasive network to support many users, locations, and applications.

Given the simultaneous impact of these trends, it is evident that a one-size-fits-all approach is no longer viable in the evolving small cell landscape. SCF's latest Market Status report highlights that small cell deployments are set to peak in 2028, reaching 9.5 million units, a significant increase from 4.6 million in 2022. By the end of the decade, the global installed base is projected to exceed 60 million units, encompassing radio heads and integrated small cells, with annual revenues for vendors and integrators expected to reach USD 4.5 billion by 2028.

Despite this shift, many small cells deployed within enterprise and private networks will continue to adhere to integrated, all-in-one designs. Meanwhile, the adoption of disaggregated architectures and virtualization is expected to

accelerate, aligning with the broader industry trend toward cloud-native deployments. These dynamics underscore the critical role of small cells in enabling scalable, high-performance connectivity in diverse environments.[3].

1.2 State of the Art Analysis

This section presents an analysis of the state of the art within the field of study of this Thesis. This analysis is divided into three parts. The first part details the definition and the evolution of the SC architecture to support URLLC, taking into consideration the efforts of O-RAN, 3GPP, and SCF. The second presents the advancements and trends used in SC, which includes Virtualization, Self Organized Network (SON), and Network Slicing. While the last part explains the critical role of integrating 5G with Time-Sensitive Networking (TSN) and outlines its evolution from 3GPP Release 15 to Releases 16 and 17, detailing the introduction of TSN-specific features, new entities, and synchronization mechanisms to support industrial applications like motion control, smart grids, and sensor data coordination.

1.2.1 Emerging Standards in SC Networks

The evolution of SCs has been significantly influenced by the specifications set forth by the O-RAN Alliance, the SCF, and 3GPP, as it is shown in Figure 1.1. These organizations aim to standardize and enhance the deployment of SCs to meet the growing demands for increased network capacity and coverage, particularly in urban and dense environments. O-RAN, with its focus on open and intelligent RAN architectures, promotes interoperability and innovation through its disaggregated, software-defined approach, enabling more flexible and cost-effective network solutions.

The O-RAN Alliance has released several key specifications relevant to SCs, starting with the O-RAN Architecture Description (O-RAN.WG1.AAD) in 2018 [4], which established the foundation for an open and disaggregated RAN. In 2019, the O-RAN Fronthaul Interface Specifications (O-RAN.WG4.CUS.0) [5] were introduced, detailing open interfaces between the Radio Unit (RU) and Distributed Unit (DU) to ensure small cell interoperability. The same year, the O-RAN Near-Real-Time RAN Intelligent Controller (RIC) (O-RAN.WG2.NRT-RIC) was released [6], enhancing small cell performance through AI-driven optimization. In 2020, the O-RAN Non-Real-Time RAN Intelligent Controller (RIC) and A1 Interface (O-RAN.WG2.NON-RT-RIC) provided long-term policy and optimization support [7]. Moreover, in 2020, the O-RAN Open Xhaul Transport (O-RAN.WG9.XHAUL) [8] specified efficient transport network connections for small cells. Finally, in 2021, the O-RAN Service Management and Orchestration (SMO) (O-RAN.WG7.SMO) [9] defined frameworks for automated deployment and management of small

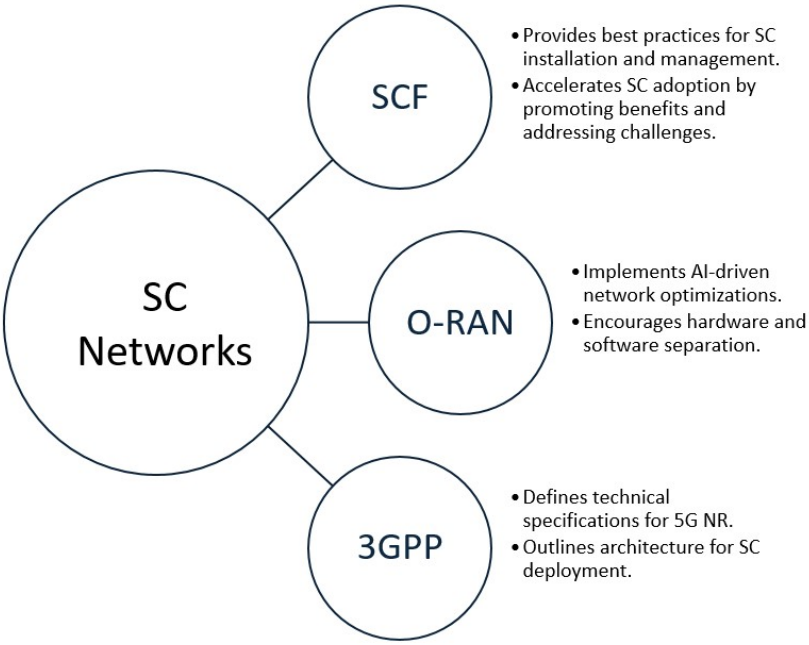

Figure 1.1: Contributors to the small cell development

cells within the RAN. These releases collectively support the integration, optimization, and management of small cells in the evolving 5G landscape.

The work of the O-RAN Alliance is complementary with SCF's work, which provides comprehensive guidelines and best practices for SC deployment, focusing on factors such as integration, performance, and scalability. Together, these specifications drive the development of advanced SCs network supporting diverse applications, including IoT, 5G, and beyond, ensuring robust, high-capacity, and low-latency connectivity.

The SCF has made significant strides in standardization efforts, as exemplified by documents such as SCF198 [10], SCF199 [11], and SCF235 [12]. SCF198 explores the convergence of 5G-era IoT use cases and enterprise small cell networks, highlighting the ongoing deployment of 4G IoT technologies and the evolving standards for 5G IoT. SCF199 delves into how small cell networks can address Ultra-Reliable Low Latency Communication (URLLC) requirements and network slicing in 5G networks, emphasizing the inter-dependency between URLLC, network slicing, and small cell evolution. SCF235 provides a foundational understanding of market trends in the Private-Small Cell Net-

work (PSCN) sector and includes surveys highlighting key adopters. According to the latest survey from SCF235, local governments are projected to be the largest adopters of private networks by 2025, leveraging them for public safety initiatives and smart city development. Other significant sectors driving adoption include manufacturing, retail, and transportation.

The standardization of small cells by 3GPP began during the development of Long Term Evolution (LTE), being part of the 3GPP Release 8, finalized in 2008. Small cells were further enhanced in subsequent releases:

- 3GPP Release 8 (2008): As the first release of LTE, it laid the groundwork for small cell technology by enhancing mobile broadband capabilities and supporting higher data rates and lower latency.
- 3GPP Release 10 (2011): It introduced LTE-Advanced, which included features like carrier aggregation and improved support for Heterogeneous Networks (HetNets), where small cells play a crucial role.
- 3GPP Release 12 (2015): Enhanced support for small cells with features such as dual connectivity allows user equipment to connect to both a macro and a small cell simultaneously.
- 3GPP Release 13 and beyond: Continued enhancements for small cells, including improved indoor positioning, enhanced Licensed Assisted Access (LAA) for unlicensed spectrum use, and further integration into 5G networks.

Over the past ten years, the wireless industry has seen significant changes, especially since the SCF first started exploring what defines a SC. However, with the advent of 5G technology, SC deployment is expected to cover a wider range of situations. The availability of new spectrum bands like sub-6 GHz and millimeter waves drives this expansion. As a result, SCF anticipated that SCs would come in various shapes, sizes, and designs, leading to more diverse form factors and architectures.

In the 5G era, a SC can handle both 4G LTE and 5G NR signals, or there can be separate SCs for 4G and 5G in the same network. A 5G NR SC follows the specifications set by 3GPP Technical Specification (TS) 38 series NG-RAN gNB, connecting to the 5G Core Network (5CN) through a 3GPP-defined interface. As shown in Figure 1.2, the setup can include an integrated gNB (on the left) or separate units called gNB Central Unit (gNB-CU) and gNB Distributed Unit (gNB-DU), connected through a split interface (on the right) [13].

A small cell network comprises small cells, which can either be integrated into a single unit or disaggregated into two or three separate products, as illustrated in Figure 1.3 and Figure 1.4 respectively. Disaggregated small cell solutions are currently undergoing standardization efforts by prominent industry bodies such as 3GPP, the SCF, and the O-RAN Alliance. Furthermore, 5G NR SC networks can support one or more SCs.

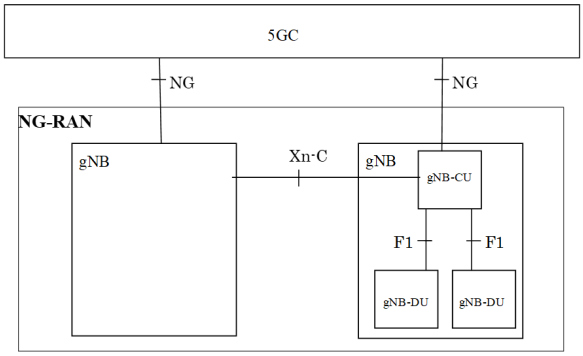

Figure 1.2: 5G NR Overall Architecture [13]

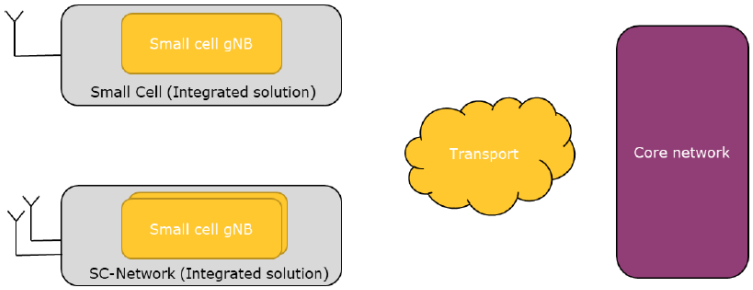

Figure 1.3: SC integrated solution [2]

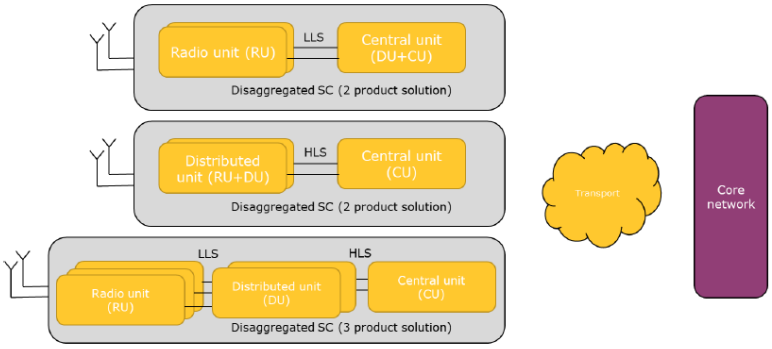

Figure 1.4: SC disaggregated solution [2]

1.2.2 Advancements and Trends in SC Technology

Advancements in SC technology are transforming the landscape of mobile networks, driven by virtualization and edge computing capabilities. Key trends include functional splits in network infrastructure, multitenancy, RAN sharing, and the implementation of SON. These innovations enhance network flexibility, efficiency, and performance, addressing the growing demands of modern communication.

- Functional Splits and Virtualization: Network infrastructure virtualization is revolutionizing SC technology. Functional splits determine which eNodeB functions can be executed in the cloud, enhancing network flexibility and optimization. The SCF has identified various functional splits for different use cases, optimizing where virtual network functions are executed relative to physical small cell functions [14].

- Multitenancy and RAN Sharing: Unlike traditional mobile operators who maintain their infrastructure, multitenancy involves shared resources among multiple operators. This fosters a dynamic and scalable market, allowing operators to focus on core business functions while outsourcing network connectivity maintenance[15]. However, multitenancy also introduces unique challenges in network planning. The management of shared RAN must accommodate varying traffic demands from multiple tenants, each with distinct characteristics such as peak hours and service types. Flexibility is crucial for efficient multi-tenancy implementation.

- Cloud-Enabled Small Cells: Mobile Edge Computing (MEC) has emerged as a crucial paradigm to address the growing resource demands of terminal devices. Integrating MEC with SC networks is essential for exponentially increasing data traffic and enhancing network coverage, positioning it as a key component of next-generation wireless networks. However, the influx of terminal devices requiring computation offloading to edge servers can lead to network congestion, degrading performance, and causing imbalance among multiple devices. To mitigate these challenges, innovative approaches such as joint admission control and computation resource allocation are being developed [16], formulated as stochastic optimization problems to ensure efficient and balanced resource distribution across the network. This integration improves service delivery and supports applications like the IoT, augmented reality, and data caching by bringing computing capabilities closer to the end users.

- SON and Network Slicing: The dense environments envisioned for SC deployment require autonomous network optimization to reduce manual intervention. SON features enable the network to dynamically adjust operational settings (e.g., transmit power, channel bandwidth, electrical

antenna tilt) and specific Radio Resource Management (RRM) parameters (e.g., admission control thresholds, handover offsets, packet scheduling weights). The development of these Self-X functions is supported by virtualized platforms using Network Functions Virtualization (NFV) and MEC technologies, significantly reducing operating costs by minimizing human errors. Moreover, virtualization in SC networks allows the partitioning of resources and capacity into multiple isolated slices tailored to different vertical markets' requirements. This customization ensures that each slice meets specific demands, improving overall network efficiency and service delivery.

1.2.3 5G and TSN Integration

The industry is experiencing a tremendous revolution since machines are no longer expected to be static and wired. Still, everything has to present an excellent capacity for reconfiguration, for which the introduction of wireless communications is strictly necessary. This is the advent of the Industrial Internet of Things (IIoT) and Industry 4.0 concepts [17]. In Industry 4.0 networks, real-time ultra-reliable communication is required to forward critical process data. However, sensors and actuators are becoming more intelligent and transmit real-time data and other data types, such as energy metrics or maintenance reports. This plethora of services and the increasing demand for reliability and capacity are pushing wireless system architectures to become more interoperable and flexible. The industry needs 5G. On the other hand, the industry has significant restrictions regarding the synchronization of the processes that take place in the factory. Some examples are given in [18]:

- Motion control and control-to-control communication for industrial controllers require less than 1 µs of offset among the time clocks used for their operation.
- Smart grid, where the synchronicity between phasor measurement units reporting must be less than 1 ms.

So far, this tight restriction has meant that industrial systems have always used specific protocols to guarantee device synchronization. The most representative initiative in this direction is TSN. From its conception, 5G was designed to respond to these two significant challenges: the wireless flexibility of Industry 4.0 and the ability to transmit at very low latency and guarantee high transmission reliability. However, in the first release of the 5G standard, Release 15, the 5G network did not include the possibility of guaranteeing two entities' synchronization using a common time source. After Release 15, the integration of TSN with the 5G system became a top priority for standardization. This is essential to achieving flexible mobility and reliable connectivity within the industry. A consensus is that Industry 4.0 will only happen after these two standards merge. Release 16 gives a solid foundation for integrating

5G and TSN [19]. In this release, the 3GPP specifies the 5G System (5GS) features for supporting TSN standards and defines new entities for translating TSN protocols into 5G internal procedures. This work can be applied in motion control and control-to-control scenarios where a controller sends a downlink timestamp to synchronize one or several actuators for executing a specific task. Complementary, Release 17 extends the TSN integration to uplink synchronization, in which the machine sensors send the timestamp to a controller or a monitoring device [20]. This use case is highly important, for example, in smart grids, for properly interpreting sensor measurements.

The introduction of new features to support TSN in 3GPP 5G Release 16 involves the integration of three key entities within the 5G system, as illustrated in Figure 1.5. Firstly, the TSN Application Function (TSN AF) plays a crucial role in facilitating communication between the 5G system and the Central Network Controller (CNC) , which is an essential entity within the TSN system. While the CNC is not explicitly depicted in the figure, it is responsible for managing and configuring TSN bridges and end-stations, ensuring time-sensitive traffic adheres to deterministic communication requirements. The TSN AF translates the control and management functions received from the CNC into 5GS-specific signaling, enabling seamless TSN-5G interworking.

Secondly, the Network Side TSN Translator (NW-TT) is integrated within the User Plane Function (UPF) and serves as the gateway for TSN traffic entering the 5G system from external networks. It ensures that time-sensitive traffic is handled with the appropriate QoS policies defined for TSN streams. Lastly, the Device Side TSN Translator (DS-TT) translates 5G messages to the Listener at the User Equipment (UE) side, assuming the UE is Time Sensitive Communication-enabled (TSC-enabled UE). This ensures that the deterministic communication requirements of TSN streams are maintained throughout the 5G system.

By integrating these entities, 5G Release 16 enables a robust TSN framework, bridging industrial Ethernet networks with 5G connectivity while ensuring precise synchronization and low-latency communication.

From a TSN perspective, the 5GS includes a TSN Bridge responsible for forwarding and updating the CorrectionField in the gPTP messages it processes. This updating process, referred to as correction in TSN terminology, is carried out by the NW-TT and DS-TT entities. In Release 16, one or more TSN Grandmaster (GM)s are connected to the network to synchronize the TSN end stations, a process termed downlink synchronization by 3GPP. Similarly, Release 17 describes the uplink time synchronization, where the TSN GM is attached to the device side to synchronize TSN end stations behind the 5GS and other UEs. This uplink synchronization is particularly important for coordinating measurements from various sensors synchronized within a controller gathering such data.

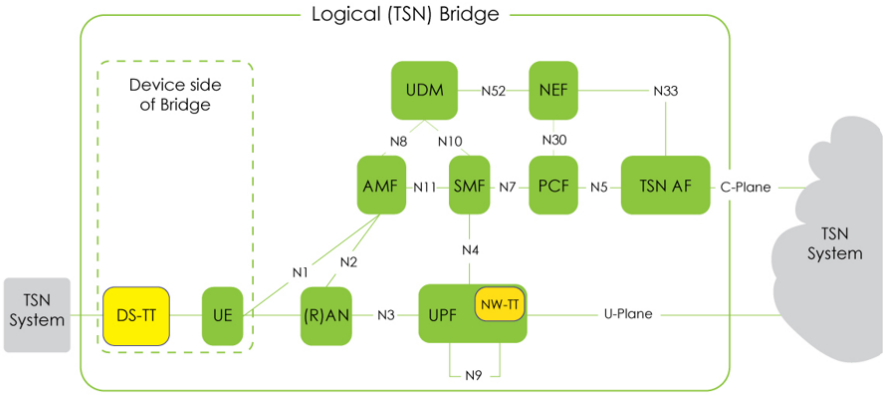

Figure 1.5: System architecture view with 5GS as TSN bridge [20]

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1.3 Problem and Thesis Scope

The standardization of 5G SC has not received sufficient attention, leading to the absence of a defined 5G system architecture that supports 5G Femtocell (Femto), the most commonly used subset of SC for private deployments. Unlike LTE, which has a comprehensive Home eNB (HeNB) system including HeNB and Home eNB Gateway (HeNB-GW), 5G lacks an equivalent Home gNB (HgNB) system comprising both HgNB and Home gNB Gateway (HgNB-GW). This gap in standardization hinders the deployment and integration of 5G Femto, limiting their potential benefits in private network environments.

However, an ongoing effort exists in SC under a study item called FS_5G_Femto, with expected outcomes in Release 19. The Service Architecture Working Group 1 (SA1) group is specifying normative requirements for Premises Radio Access Station (PRAS) as part of the PIRates Work Item Description (WID), focusing on enabling access control for 5G Femto. Justifications for the study objectives include the cost-effective improvement of 5G indoor coverage and enhanced support for enterprise mobility [21]. With 80% of mobile sessions occurring indoors and limited 5G mid and high-band coverage, there is a need for solutions enabling end-user plug-and-play functionality and customized access control using the Closed Access Group (CAG) concept, used to identify a group of subscribers permitted to access specific cells. Additionally, high bandwidth and throughput are essential for new immersive applications such as Augmented Reality (AR), Virtual Reality (VR), e-sports, UHD 8K video, telepresence, remote meetings, and HD surveillance and indutrial automation. However, the study will focus only on defining an access control mechanism for 5G Femto deployments by using the CAG concept and enabling the provisioning of subscribers allowed to access 5G Femto within a CAG. Hence, integrating TSN with 5G does not discuss using the

5G Femto. This omission means that while the research focuses on enhancing access control for 5G Femto through CAG, it does not explore how TSN functionalities could be applied or adapted within 5G Femto environments. Consequently, any potential implications of using TSN in 5G Femto networks, such as ensuring deterministic latency or synchronized communications, fall outside the scope of 3GPP study.

This lack of standardization becomes even more critical when considering advances in robotics and automation, which have revolutionized industrial processes by enabling highly configurable equipment with advanced capabilities. However, equipment requiring dexterous functions often necessitates the exchange of large volumes of data with low latency. Traditionally, wired connections have facilitated high-bandwidth synchronization between devices by synchronizing the local clocks of different network components, forming a virtual clock domain [22] [23]. This domain represents a common reference time for synchronized operation. Yet, wired communication may be impractical in scenarios involving dynamic or mobile equipment, limiting mobility and flexibility. The advent of 5G networks promises high bandwidths capable of handling substantial data transfers, potentially facilitating synchronization between robotic network components [24]. However, wireless communication introduces additional delays compared to wired protocols, posing challenges for precise synchronization [25][26]. These delays, including transmission and processing delays, can compound synchronization deviations, impacting the accuracy of coordinated actions between devices. In industrial settings, accurate time information is critical for synchronous communications, with stringent requirements for clock synchronicity to ensure operational efficiency [18]. As processes become more complex, the demand for real-time data increases, necessitating the integration of diverse data types, such as energy metrics and maintenance reports, for comprehensive process monitoring. However, the challenge does not lie solely in ensuring high accuracy but also in accommodating both TSN-capable and non-TSN-capable devices, particularly given the prevalence of legacy devices in industrial settings. Addressing this issue is crucial for achieving seamless and practical synchronization solutions across diverse IoT landscapes.

SC was not addressed in the TSN integration with 5G. The 3GPP's proposed solution for TSN involves a standard gNB without additional capabilities. This can be attributed to the lack of architecture supporting 5G NR SC so far, which also implies the absence of HgNB-GW standards—unlike the situation with 4G SC.

The problem presented has motivated in this Thesis the identification of several hypotheses:

- Hypothesis 1: integrating SC into 5GS enhances network coverage, reduces latency, and increases network capacity, enabling real-time data transmission critical for automated industrial processes.

- Hypothesis 2: integrating SC enables seamless handover between different Radio Access Technologies (RAT) and efficiently allocates network resources through network slicing.

- Hypothesis 3: Implementing SC gateways as controllers in dual connectivity scenarios will significantly reduce signaling complexity while maintaining compatibility with legacy systems.

- Hypothesis 4: Moving the TSN translator to the SC instead of the device can ensure high accuracy for IoT devices that are not TSN-capable.

- Hypothesis 5: This TSN-enabled SC can use the physical layer signal of the 5G radio frame and the transmission of the GM reference time to provide high-precision synchronization.

- Hypothesis 6: The UE-GM synchronization occurs within an exceptionally narrow timeframe as small as 10 ns.

1.4 Thesis Objectives

This thesis addresses the gaps in 5G SC standardization, particularly focusing on integrating SCs into cellular networks with a lean approach that reduces impact thanks to SC gateways and enhances performance with Time-Sensitive Networking (TSN) capabilities.

The main objective of the research can be divided into several sub-objectives listed below:

- Investigate the potential of small cell integration to enable seamless handover between different RAT and optimize network resource allocation through network slicing.

- Assess the effectiveness of implementing SC gateways as controllers in dual connectivity scenarios, reducing signaling complexity while ensuring compatibility with existing legacy systems.

- Explore the feasibility of relocating the TSN translator functionality to the SC instead of the device, aiming to achieve high accuracy for IoT devices lacking native TSN support.

- Investigate the capabilities of TSN-enabled small cells in utilizing the physical layer signal of the 5G radio frame and the transmission of GM reference time for providing high-precision synchronization.

- Evaluate the synchronization performance of UE with GM clocks within exceptionally narrow timeframes, potentially as precise as 10 nanoseconds, facilitated by TSN-enabled small cells.

1.5 Thesis Outline

This Thesis is organized into seven chapters, as described below:

Chapter 2 Literature review

Chapter 3 Key Technologies for the Advent of the 6G

Chapter 4 The Small Cell integration into a 5G Network

Chapter 5 Enhanced Time Synchronization in 5G Private Networks with Time Sensitive-Enabled Small Cell

Chapter 6 5G Physical Layer-Based Procedure to Support Time Sensitive Networking

Chapter 7 draws the conclusions of the Thesis and describes the future lines of research.

1.6 Thesis Publications

The work developed during this thesis made the following publications possible.

Journals

[J1] **Bouchmal F**, Carrasco O, Fu Y, Rodrigo J, Monserrat JF, Cardona N. 5G Physical Layer-Based Procedure to Support Time-Sensitive Networking. In Telecom 2024 Jan 24 (Vol. 5, No. 1, pp. 49-64). MDPI.

[J2] Monserrat JF, **Bouchmal F**, Martin-Sacristan D, Carrasco O. Multi-radio dual connectivity for 5G small cells interworking. IEEE Communications Standards Magazine. 2020 Sep 23;4(3):30-6.

[J3] Ortega V, **Bouchmal F**, Monserrat JF. Trusted 5G vehicular networks: Blockchains and content-centric networking. IEEE Vehicular Technology Magazine. 2018 Apr 20;13(2):121-7.

[J4] Fu Y, Navarro JR, Monserrat JF, **Bouchmal F**, Carrasco O. Performance Evaluation of a Minimum Mean Square Error-based Physical Sidelink Share Channel Receiver under Fading Channel.World Academy of Science, Engineering and Technology International Journal of Information and Communication Engineering Vol:18, No:1, 2024 .

Conferences

[C1] **Bouchmal F**, J. F. Monserrat, J. Vicente and O. Carrasco, "Implementation of Network Slicing for the 5G Small Cells Integration," 2019 IEEE Wireless Communications and Networking Conference (WCNC), Marrakesh, Morocco, 2019, pp. 1-6, doi: 10.1109/WCNC.2019.8885502.

[C2] Monserrat JF, Martin-Sacristan D, **Bouchmal F**, Carrasco O, de Valgas JF, Cardona N. Key technologies for the advent of the 6G. In 2020 IEEE wireless communications and networking Conference Workshops (WCNCW) 2020 Apr 6 (pp. 1-6). IEEE.

[C3] Y. Fu, J. R. Navarro, **Bouchmal F**, J. F. Monserrat and O. C. Quilis, "Low Complexity Soft Demapper for MIMO Sidelink Communications," 2024 IEEE Middle East Conference on Communications and Networking (MECOM), Abu Dhabi, United Arab Emirates, 2024, pp. 117-122, doi: 10.1109/MECOM61498.2024.10881052.

Book Chapter

1. Monserrat JF, Vicente J, **Bouchmal F**, Carrasco O. On the Support of NFV: Available Tools and Solutions.Wiley 5G Ref: The Essential 5G Reference Online, pp. 1-21, 2019.

Patent

1. Carrasco O, **Bouchmal F**, 5G small cell time synchronized networking, US Patent US20230156647A1, 2022.

2. Carrasco O, **Bouchmal F**, Femtocells for Wireless Communication Coverage, US Patent US20240155375A1, 2023.

Chapter 2

Literature Review

2.1 Overview of 5G and 6G Technologies

2.1.1 Introduction

The rapid evolution of mobile communication technologies from 4G LTE to 5G, and the anticipated development of 6G, marks significant progress in telecommunications. 5G, launched globally in 2019, represents a leap in connectivity, offering higher data rates, lower latency, and the ability to simultaneously support a massive number of devices. As 5G continues to expand globally, researchers are already looking toward the next generation: 6G, expected to launch around 2030. This section analyzes the state of the art of 5G and 6G technologies, their key features, and emerging use cases across various sectors.

2.1.2 5G Technologies

5G, the fifth generation of mobile communication technology, represents a significant leap forward from its predecessor, 4G LTE. Launched globally in 2019, 5G is designed to provide enhanced connectivity, offering higher data rates, ultra-low latency, improved network efficiency, and the ability to connect many devices simultaneously. Key features of 5G include [27]:

- Enhanced Mobile Broadband (eMBB): 5G offers significantly higher data speeds, reaching up to 10 Gbps, which is crucial for applications like high-definition video streaming, Virtual Reality (VR), and Augmented Reality (AR).

- Ultra-Reliable Low-Latency Communications (URLLC): With latency as low as 1 millisecond, 5G enables mission-critical applications such as autonomous driving, remote surgery, and industrial automation, where real-time communication is essential.

- Massive Machine-Type Communications (mMTC): 5G supports the Internet of Things (IoT) by connecting millions of devices per square kilometer. This capability is vital for smart cities, smart homes, and industrial IoT applications.
- Network Slicing: 5G allows the creation of virtual networks tailored to specific use cases, offering customized service levels for different applications, such as autonomous cars or e-health services.
- New Spectrum Utilization: 5G operates across a wide range of frequencies, from sub-6 GHz to Millimeter Wave (mmW) bands, providing higher capacity and speed for users.

Moreover, one of the most exciting prospects for 5G is its use in local networks for industrial applications. In Japan, for example, the concept of Local 5G is being developed to address the specific needs of industrial sectors [28]. This would allow industries to deploy private 5G networks that meet their unique high reliability and security demands. As 5G evolves, it is expected to enhance uplink performance, ensuring that industrial systems can reliably upload vast amounts of data, such as high-definition video, in real-time.

The main use cases of 5G can be summarized as follows:

- Industrial Applications and Local 5G: The concept of Local 5G is gaining traction, especially in regions like Japan, where industrial sectors demand reliable and secure private networks. Local 5G networks allow industries to build their own 5G infrastructure to meet specific requirements, such as ensuring real-time data transmission and high-definition video uploads in manufacturing, logistics, or energy management environments.
- Autonomous Vehicles: The low-latency and high-reliability features of 5G make it critical for the success of autonomous vehicle ecosystems. Real-time communication between vehicles, infrastructure, and the cloud ensures safety and efficient navigation.
- Smart Cities and IoT : The massive Machine Type Communications (mMTC) capability of 5G supports smart city applications, including connected traffic systems, waste management, and environmental monitoring. These applications require a vast network of sensors and devices that 5G's high-capacity network can handle effectively.
- Healthcare: In healthcare, 5G supports telemedicine, remote diagnostics, and even remote surgery, where real-time data transmission and communication are paramount.

2.1.3 6G Technologies

Though still in its research phase, 6G is expected to build on the foundation laid by 5G, pushing the boundaries of mobile communication even further. 6G

is anticipated to launch around 2030 and will address the growing demands for even faster, more efficient, and ubiquitous connectivity. Some key aspects of 6G include [29]:

- Terahertz Frequencies: 6G will likely operate in the Terahertz (THz) frequency range, offering massive bandwidth and enabling unprecedented data transfer rates, potentially exceeding 100 Gbps. This will support highly demanding applications like immersive holographic communications and advanced AI-driven services.
- AI and Machine Learning Integration: 6G networks are expected to incorporate Artificial Intelligence (AI) and Machine Learning (ML) technologies deeply into the network architecture. This will enable smarter and more adaptive networks, capable of self-optimization, predicting traffic demands, and enhancing network performance autonomously.
- Extreme Latency and Reliability: Building on the low-latency capabilities of 5G, 6G will aim for near-instantaneous communication with latency in the microsecond range. This will enable real-time interactions in applications such as autonomous systems, robotics, and human-computer interfaces.
- Advanced IoT and Ubiquitous Connectivity: While 5G enables mMTC, 6G will extend IoT capabilities, allowing the seamless integration of connected devices across various environments, including urban, rural, and even remote areas. It will enhance smart city infrastructure, healthcare, agriculture, and industrial automation.
- Sustainability and Energy Efficiency: 6G aims to be highly energy-efficient, addressing the growing need for sustainable technologies. Researchers are focusing on designing energy-efficient hardware and optimizing resource usage, minimizing the environmental impact of large-scale deployments.
- Human-Centric Networks: 6G is expected to focus on human- and society-centered applications, including brain-computer interfaces, advanced health monitoring systems, and immersive telepresence experiences. The convergence of the digital and physical worlds through 6G will enable new forms of communication and interaction, pushing the boundaries of what is possible.

As 6G continues to develop, the envisioned use cases for this next-generation technology highlight its transformative potential across multiple sectors. These use cases build on the advancements of 5G, enhancing both the speed and functionality of connectivity:

- Holographic Communication and Augmented Reality (XR): 6G's extremely high data rates and low latency will enable real-time holographic

communication, allowing for fully immersive virtual meetings, remote collaboration, and entertainment experiences XR, which combines virtual, augmented, and mixed reality, will reach new levels of immersion with 6G.

- Brain-Computer Interfaces (BCI): With 6G's ultra-low latency and high reliability, BCIs will allow direct communication between the human brain and external devices, potentially revolutionizing medical treatment, human augmentation, and cognitive enhancement.

- Global Connectivity: 6G's ubiquity will ensure no region is left without reliable high-speed internet. This will have profound implications for global trade, remote work, and educational access, enabling a more connected and inclusive world.

2.2 Network Function Virtualization (NFV)

2.2.1 Introduction

The virtualization of mobile networks represents a significant shift in how telecommunication infrastructures are designed, deployed, and managed. This paradigm change is critical for enabling 5G networks, which demand flexibility, scalability, and cost-efficiency. The literature emphasizes the theoretical frameworks and technical advantages of virtualization, particularly in terms of its foundational technologies like Infrastructure-as-a-Service (IaaS), Network Functions Virtualization (NFV), and Software-Defined Networking (SDN). However, less has been written about the practical implementation of these concepts, especially at the network's edge, where fog computing plays an essential role in reducing latency and improving performance.

2.2.2 IaaS and Cloud Computing

The evolution towards IaaS in mobile networks centers on offering scalable, on-demand infrastructure that no longer depends on dedicated hardware. Technologies such as OpenStack, Docker, and Kubernetes have a significant role in enabling flexible cloud environments capable of hosting various network functions. These technologies enable operators to automate tasks, often using solutions like Terraform, which provide soft portability—allowing deployments to be easily recreated in different IaaS environments using appropriate plugins. This aligns with the approach highlighted in the text, where the implementation simplifies automation and portability.

The transition to cloud computing is driven by the the Control and User Plane Separation (CUPS) principle in 5G architecture, which allows operators to deploy control and user plane functions on general-purpose hardware. This reduces operational costs and enables dynamic scaling of networks based on

real-time demand rather than peak load conditions. This shift aligns with the broader literature on virtualization, where NFV and SDN help decouple software from hardware, increasing flexibility and efficiency in network management [30].

2.2.3 Fog Computing: Extending the Cloud to the Edge

Fog computing extends cloud capabilities to the network's edge, especially to base stations and cells, improving performance and reducing latency. It enhances real-time applications, such as those required by IoT devices, by pre-processing data at the edge before sending aggregated results to the cloud [31]. This approach enables more efficient resource use while reducing latency, as noted in [32], who discuss the importance of fog and edge computing for low-latency applications in 5G networks .

Fog computing also supports the scalability of 5G infrastructure, particularly about Remote Radio Unit (RRU), which operates on lighter hardware and reduced latency. In [33], the authors emphasize the importance of fog computing for 5G networks, noting that it allows the distribution of computing resources closer to users, thus enhancing the responsiveness of the network.

2.2.4 Network Virtualization and Slicing

Virtualization is a key enabler for 5G networks, offering resource allocation and function deployment flexibility. NFV decouples network services from dedicated hardware, enabling general-purpose computers to run multiple network functions.NFV, combined with SDN, centralizes network management, making it easier to adapt to changes in network demand and increase overall efficiency [30].

Network slicing further enhances the flexibility of virtualized 5G networks by creating multiple virtualized network instances tailored to specific use cases. In [34], the authors highlight how network slicing can dynamically allocate resources across different slices based on real-time needs, optimizing the use of available infrastructure. This approach aligns with the Network Slice Selection Function (NSSF), which orchestrates the distribution of virtualized network functions across nodes.

2.3 Time Sensitive Networking (TSN)

2.3.1 Introduction

The integration of Time-Sensitive Networking (TSN) with 5G networks is gaining momentum as the demands of Industry 4.0 and industrial automation increase. These environments require highly reliable and precise communications, particularly for applications involving robotics, factory automation, and

other Industrial IoT scenarios. Achieving real-time communication with minimal delays is crucial for maintaining synchronization across different network components, especially when the components are mobile and reconfigurable.

TSN, based on the IEEE 802.1 working group specifications, was originally designed to enable deterministic communication over Ethernet. It ensures that data streams are delivered on time and without loss. As 5G technology evolves, it offers the potential to extend TSN capabilities into wireless domains, where deterministic communication is critical for the precise coordination of industrial processes. TSN enables devices to maintain synchronized clocks and supports low-latency, time-sensitive data transmission.

To support these requirements, 3GPP introduced significant TSN-related enhancements in Release 16 and Release 17, which paved the way for seamless integration of TSN into 5G networks. Release 16 laid the foundation by integrating key TSN elements, allowing 5G networks to bridge wired TSN domains and wireless 5G components. Release 17 further improved this by enhancing uplink synchronization, which is critical for applications such as real-time monitoring and control in smart grids and advanced manufacturing processes.

These advancements involve two key features:

- TSN Translators: These are critical to adapting TSN protocols to 5G's internal procedures. They ensure the 5G system can emulate TSN functionalities, such as time synchronization, over a wireless network.
- End-to-End Synchronization: 5G networks, in collaboration with TSN, achieve clock synchronization through precision time protocols, enabling devices to remain synchronized within a very narrow time window (as small as 1 µs). This is achieved by leveraging the physical layer capabilities of 5G, such as the slot indication signals embedded within 5G radio frames.

2.3.2 Configuration Methods in 3GPP Standards

In the evolution of 5G technology, precise time synchronization has become essential for various applications, including critical infrastructure, synchronized media playback, and machine learning time-stamping. Traditionally, GNSS (Global Navigation Satellite Systems) provided timing for mobile devices. Still, there has been a growing demand for terrestrial solutions, especially in environments where Global Navigation Satellite Systems (GNSS) signals are unreliable due to interference, jamming, or spoofing. To address this, 3GPP has introduced multiple time synchronization mechanisms from Release 16 to Release 18.

- Method a): 5G as a Time-Aware System: This method integrates 5G with IEEE TSN networks. In this setup, the TSN domain uses its clock domain, and the Generalized Precision Time Protocol (gPTP) distributes

the time from a Grandmaster (GM) clock to various receivers. The 5G System (5GS) acts as a bridge between the TSN network and connected devices, allowing time-aware communication between TSN devices and the 5G network. This integration facilitates high-precision synchronization in environments that require exact timing, such as industrial automation or automotive networks.

- Method b): 5G as a PTP Instance: In this approach, the 5GS functions as a Precision Time Protocol (PTP) node within a PTP network. Two possible configurations exist. First, PTP Boundary Clock where the 5GS serves as a time source, maintaining the Precision Time Protocol (PTP) timescale and distributing the synchronized time to other devices. Second, as a PTP Transparent Clock where the 5GS corrects PTP messages by calculating the residence time, which is the duration it takes for PTP messages to travel through the system. This ensures accurate time propagation through the 5GS.

- Method c): Direct Time Synchronization Over the Air Interface: This method allows the 5G Next Generation Radio Access Network (NG-RAN) to transmit time information directly to UE via the air interface. The timing information is usually in Coordinated universal Time (UTC) and is tied to a recognizable event, such as a system frame boundary so that the UE can easily align its internal clocks. Reference Time Information (RTI) is either broadcast using System Information Block 9 (SIB9) or sent via dedicated Radio Resource Configuration (RRC) messages. The particularity of this method is that the UE can use SIB9/RRC timing information to align its internal clock without TSN functionality.

For methods a) and b), 3GPP incorporated IEEE specifications, which introduced two functional entities: The Device Side TSN Translator (DS-TT) on the UE side and the Network Side TSN Translator (NW-TT) on the 5G network side.

The management of these translators, initially introduced in Release 16, was handled by the TSN Application Function (TSN AF) TSN Application Function (TSN AF). In Release 17, the Time-Sensitive Communication Time Synchronization Function (TSCTSF) replaced the TSN AF. The TSCTSF provides configuration control over the DS-TT and NW-TT while offering enhanced functionality for time-sensitive communication, such as improved Quality of Service (QoS) and the ability to meet strict timing requirements. Third Generation Partnership Project (3GPP) has given significant attention to direct monitoring and reporting of timing synchronization over the air interface (method c). This was highlighted in Technical Report (TR) 23.700-25 [35], which proposes a mechanism whereby the gNB sends a report ID via SIB to notify UEs of new synchronization status reports. UEs can retrieve the synchronization information by switching to the RRC Connected state or using the report ID to determine the status automatically.

This method, while promising, has some limitations:

- It does not support external time domains like TSN.
- The synchronization accuracy is limited to around 5-10 microseconds, which may not be sufficient for highly time-sensitive applications. Despite these limitations, method c) is expected to be widely adopted due to its simplicity and applicability in various 5G use cases.

Chapter 3

Key Technologies for the Advent of the 6G

As we look beyond the early stages of 5G and into the future of 6G, several technological breakthroughs are expected to emerge, addressing both the challenges and opportunities for advancing global connectivity. These developments will support new use cases and redefine the architecture of communication systems. In this chapter, we explore the potential use cases enabled by 6G, examining how emerging technologies like Ultra-Reliable and Low Latency Communications (URLLC) and ultra Mobile Broadband (uMBB) will reshape industries, drive innovation, and meet the needs of an increasingly connected world. From holographic calls to intelligent automation in smart cities, these use cases highlight the versatility and transformative power of 6G. Additionally, we will delve into the role of Virtual Small Cell (VSC) in enabling high-capacity, low-latency communication in dense environments, addressing the critical challenges of mobility and resource management.

3.1 Use Cases

The deployment of 6G networks will support a variety of new use cases that extend beyond traditional mobile broadband applications. The envisioned use cases include ultra-high-speed communications, immersive experiences like virtual reality and holographic calls, and advanced applications such as remote medical procedures and cooperative robotics. A significant advancement will be in the development of Augmented Reality (AR)and Virtual Reality (VR), with uMBB enabling high-definition content delivery and real-time interactions, making applications like telepresence and immersive gaming a reality.

6G will also enhance URLLC capabilities. This will benefit critical sectors such as transportation with autonomous vehicles and industrial automation with cooperative robotics. For example, factory precision motion control will

enable robots to perform synchronized tasks without requiring physical connections, providing a significant leap in manufacturing productivity. Moreover, sensor-rich environments and smart grids will become pervasive, allowing for real-time data-driven infrastructure and utility management decisions.

Figure 3.1 presents a speculative projection of 6G services, arranged across three axes that reflect the core characteristics of these services: uMBB, ambient internet, and enhanced ultra-reliable low-latency communication (eURLLC). From my point of view, holographic calls will be the killing application in 6G.

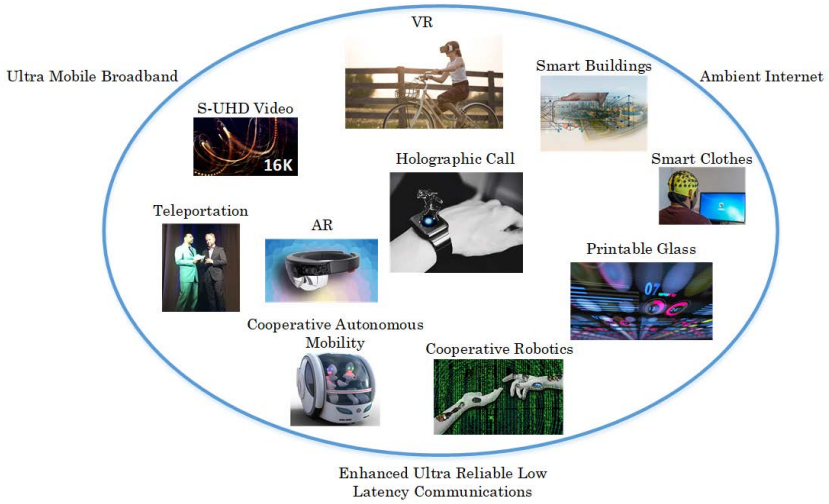

Figure 3.1: Use cases envisioned for 6G organized according to dimensions of UMBB, Ambient Internet and eURLLC

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3.2 Virtual Small Cells

3.2.1 Enablers of Virtual Small Cells

As we approach the era of 6G, new technological innovations are paramount in driving connectivity and efficiency to unprecedented levels. One of the key advances enabling this vision is the concept of VSC, which offers a flexible, virtualized solution for improving communication in dense urban environments.

A VSC is a dynamically created, virtualized communication entity that operates as a localized small cell. Unlike traditional fixed small cells, VSCs can be deployed on-demand and are not bound to static infrastructure. These cells function as autonomous networking units equipped with radio resource management, computing, and storage capabilities. A VSC can be hosted by any 6G-enabled device, acting as a base station or an access point for nearby

users. The uniqueness of VSCs lies in their ability to form temporary networks with neighboring devices, optimizing connectivity and reducing the overall network burden.

By relying on emerging computing paradigms such as Network Functions Virtualization (NFV) and Software-Defined Networking (SDN), VSCs reduce latency, increase scalability, and efficiently offload traffic from overloaded macrocells. This makes them ideal for future 6G networks where dynamic, high-speed, and localized communication is required [36]. The implementation of VSCs heavily relies on virtualization, a technology that allows physical network resources to be abstracted and managed through software. In the 6G context, virtualization enables VSCs to dynamically allocate and optimize resources such as radio frequency spectrum, computational power, and network bandwidth across multiple service providers and users.

- NFV: NFV is crucial in enabling VSCs to perform a wide array of network functions, such as routing, firewalls, and load balancing, in a virtualized environment. This allows network operators to deploy virtualized base stations or small cells without dedicated hardware, significantly reducing capital and operational expenses (CAPEX and OPEX). NFV also provides resource sharing across multiple network operators, ensuring seamless communication and reducing the need for infrastructure duplication.

- SDN: SDN complements NFV by providing centralized control over the network's data flows, making it easier to manage and reconfigure VSCs based on demand. SDN controllers dynamically adjust the allocation of computation, communication, caching, and control (4C) resources to adapt to changing network conditions. This creates a flexible and programmable network, allowing VSCs to respond to real-time traffic changes, optimize bandwidth usage, and ensure low-latency communication.

- Virtual RAN (vRAN): Virtualization within VSCs extends to the Radio Access Network (RAN), where virtual Base Band Unit (BBU)s can be deployed in the edge or in central data centers. These BBUs handle baseband processing for the small cells and can be distributed throughout the network to manage varying traffic loads efficiently. By virtualizing the RAN, VSCs can dynamically adjust their computational load and network resources, ensuring that they meet the demands of 6G services like ultra-reliable low-latency communication URLLC and Enhanced Mobile Broadband (eMBB).

The introduction of virtualization in VSCs offers several key advantages:

- Scalability: Virtualization allows VSCs to be deployed as needed, scaling the network infrastructure up or down based on demand. This is espe-

cially useful when communication needs fluctuate, such as during large public events or in densely populated urban areas.

- Cost Efficiency: By reducing the need for physical infrastructure and enabling the dynamic sharing of resources among multiple operators, virtualization lowers both CAPEX and OPEX. This cost reduction is crucial for operators supporting 6G's extensive infrastructure requirements.
- Performance Optimization: Virtualization enhances the performance of VSCs by enabling on-demand resource allocation. SDN and NFV dynamically assign bandwidth, computing power, and storage based on the real-time needs of users and devices, ensuring optimal network performance even under heavy loads.
- Enhanced Reliability and Security: Virtualized VSCs can quickly recover from failures by shifting workloads to alternative resources in the network. Additionally, the distributed nature of the architecture enables enhanced security mechanisms, such as network slicing, where resources are isolated and securely managed for different users and applications.

3.2.2 Overcoming Mobility and Resource Challenges with HgNB-GW in Small Cells

While the virtualization of Small Cell (SC)s presents immense opportunities, it also introduces several challenges:

- Mobility Management: Since VSCs are dynamic and cover smaller areas, traditional handover mechanisms used in fixed small cells or macrocells are insufficient. New solutions must be developed to handle frequent handovers efficiently without increasing latency or power consumption.
- Complexity of Resource Management: VSCs require sophisticated algorithms to manage shared resources across different Radio Access Technologies (RAT) and multiple operators. This includes spectrum allocation, computation resource distribution, and energy-efficient operations.

This thesis introduces the concept of the Home gNB Gateway (HgNB-GW) as a crucial element in addressing several challenges encountered in integrating small cells into 5G networks. This solution will be thoroughly explored in Chapter 4, "The Small Cell Integration into a 5G Network." The HgNB-GW offers significant advantages, particularly in overcoming the key challenge of mobility management.

One of the primary challenges in deploying small cells is the efficient handling of mobility when users move across different coverage areas. Small cells typically have smaller coverage footprints, leading to more frequent handover events as users transition between cells. These frequent handovers can introduce latency and disrupt service continuity, which is critical for maintaining the

performance standards expected in 5G and future 6G networks. Additionally, mobility challenges are not limited to user devices; small cells themselves may be mobile in certain scenarios, such as those installed in vehicles, drones, or temporary infrastructure. These mobile small cells introduce additional complexities, including dynamic topology changes, fluctuating interference conditions, and the need for seamless coordination with the broader network to ensure reliable connectivity. Addressing both user and small cell mobility is essential for optimizing network performance in highly dynamic environments.

The HgNB-GW is designed to address these mobility challenges by acting as a centralized gateway for managing and coordinating small cells in the network. By introducing a hierarchical structure with the HgNB-GW at the core, the network can intelligently manage handovers and maintain service continuity across a dense deployment of small cells. This gateway reduces the signaling overhead associated with frequent handovers and enables more efficient resource allocation by centralizing the control and coordination of the small cells.

Furthermore, the HgNB-GW facilitates seamless integration of small cells into the broader 5G infrastructure by providing interfaces to the 5G core network and ensuring that small cells can function in tandem with larger macrocells. This creates a cohesive, multi-layered network architecture where small cells can offload traffic from macrocells while providing enhanced data capacity in high-density areas and ensuring smooth transitions as users move across different coverage zones.

3.3 Cell-Less Deployment

3.3.1 Challenges of the Cellular Model

The cellular model, despite its long-standing effectiveness, faces several challenges as mobile communication evolves:

- Inter-cell interference: When a user is at the edge of a cell, they experience a higher likelihood of interference from neighboring cells, leading to reduced quality of service, especially in dense urban areas where multiple cells are nearby. Techniques like cell coordination (e.g., coordinated multi-point transmission) have been proposed to mitigate these effects. Still, complexity and insufficient ultra-dense deployment in current systems have limited their real-time implementation.

- Handover Latency: The traditional model relies heavily on handovers between cells when users move across cell boundaries. Although typically quick, these handovers introduce latency and the potential for dropped connections, which can significantly affect services requiring real-time communication, such as autonomous vehicles or AR applications.

- Scalability: As mobile networks densify to accommodate growing user demand, the need for more cells with smaller coverage areas (e.g., femtocells, picocells, attocells, and even zeptocells) increases, complicating the network architecture. More base stations mean more handovers, higher signaling overhead, and more complex management of resources and interference.

6G networks will move towards a cell-less deployment model, focusing not on individual cells but on a user-centric network experience. In this model, users will no longer be tied to a specific cell but will instead connect to a distributed RAN that allocates resources dynamically based on demand. This will be achieved through dense deployment of small cells—such as femtocells, picocells, and even smaller units like attocells and zeptocells—that can communicate and share resources seamlessly. This concept eliminates the boundaries between cells, reducing handover latency and improving network efficiency, especially in environments where high mobility or ultra-dense user presence is expected.

Moreover, SC will play a crucial role in 6G by ensuring reliable indoor and outdoor coverage, particularly in urban areas where coverage gaps might exist in traditional macrocell deployments. The small cell-based architecture will enable seamless connectivity and superior user experience by reducing the distance between access points and users, thereby supporting higher data rates, lower latency, and better energy efficiency.

3.3.2 The Mechanics of Cell-Less Deployment

In a cell-less deployment, multiple Transmission Reception Point (TRP)s collaborate to serve a single user device. Instead of moving from cell to cell, a user's connection is handled by a RAN pool consisting of a distributed network of small, interconnected TRPs. These TRPs dynamically allocate resources and adjust transmission based on user demand, network load, and signal quality. The user device is no longer assigned to one specific cell; instead, it is connected to multiple TRPs simultaneously, which work in unison to provide the best possible signal and bandwidth.

Figure 3.2 illustrates the cell-less deployment concept, where macrostations have been ignored on purpose to highlight the key role of short-range stations, new roles of user devices, indoor-to-outdoor coverage, multi-hopping, high-throughput satellites, and unmanned aerial stations.

Key characteristics of a cell-less deployment include:

- Dynamic Resource Allocation: The network assigns resources based on real-time user needs and network conditions rather than fixed cell boundaries. If one TRP is experiencing high load or interference, the user device can instantly be served by another TRP, ensuring continuous and optimal service.

Figure 3.2: Cell-less deployment concept

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- Seamless Handover-Free Connectivity: As users move through the network, they remain connected to the RAN pool rather than switching from one cell to another. This eliminates the need for traditional handovers, drastically reducing latency and the risk of dropped connections. This seamless connectivity is particularly important for high-mobility applications such as connected vehicles and drones.

- Coordination Between TRPs: TRPs within the same RAN pool coordinate with each other to avoid interference and ensure efficient spectrum use. This coordination allows the network to behave as a single, cohesive unit rather than a collection of individual cells. Users at the edges of the coverage area of one TRP can be served by neighboring TRPs without experiencing the inter-cell interference typically associated with traditional cellular networks.

- Multi-TRP Transmission: In a cell-less deployment, a user device can be served by multiple TRPs simultaneously, improving signal quality and increasing data throughput. This is especially beneficial in scenarios where users are moving rapidly, such as in autonomous vehicles or high-speed trains, as the device remains connected to multiple TRPs at once, ensuring a strong, stable connection.

- Increased Spectrum Efficiency: By distributing the load across multiple TRPs and avoiding rigid cell boundaries, the network can make more

efficient use of available spectrum. Frequency reuse is optimized, and the risk of congestion in high-traffic areas is minimized.

The cell-less model brings several advantages over traditional cell-based architectures, making it a crucial component of future 6G networks:

- Improved User Experience: Users benefit from consistent, high-quality service without experiencing the dips in performance typically associated with handovers or inter-cell interference. This is particularly important for applications requiring real-time, ultra-low-latency communication, such as AR, VR, and autonomous systems.

- Scalability: Cell-less networks offer a more scalable solution as demand for mobile data continues to grow, particularly in dense urban environments. Rather than deploying more cells and managing increasingly complex handover scenarios, network operators can deploy additional TRPs as needed, each contributing to the RAN pool without the need for complex handover management.

- Better Indoor and Outdoor Coverage: Cell-less deployment enhances both indoor and outdoor coverage by leveraging dense networks of small cells (such as femtocells, picocells, attocells, and femtocells) that can seamlessly provide coverage in areas where traditional macrocells struggle, such as inside buildings or urban canyons. Additionally, the network can use capacity from indoor TRPs to serve outdoor users, creating a more flexible and adaptive coverage system.

- Reduced Latency: The absence of handovers and the ability to dynamically allocate resources among multiple TRPs significantly reduce network latency, making it possible to achieve ultra-low latency communication, which is crucial for time-sensitive applications such as autonomous driving, industrial automation, and remote medical procedures.

3.4 Network Everywhere and Federated AI-Based Network

The 6G vision foresees a world where networks are available everywhere, seamlessly integrated into everyday objects. This concept is called "network everywhere," where antennas, sensors, and communication devices are ubiquitously distributed across homes, vehicles, urban infrastructure, and even clothing. By distributing access points across the environment, 6G will ensure that connectivity is always available, whether indoors, outdoors, or in remote areas.

A critical aspect of achieving network ubiquity is the introduction of technologies like radio-stripes, which consist of long antenna arrays embedded in surfaces such as walls, windows, or even roads. These antennas will provide

coverage at very short distances, ensuring strong and reliable connections. The network-everywhere concept also enables the use of new frequency bands, such as Terahertz (THz) waves, which are key to achieving ultra-high data rates in future wireless networks. THz frequencies (ranging from 0.1 to 10 THz) offer significantly wider bandwidths compared to mmWave and sub-6 GHz bands, allowing for the transmission of extremely large amounts of data per unit time. This expanded bandwidth directly translates into higher data rates, making THz waves an essential enabler for applications requiring multi-gigabit-per-second speeds, such as holographic communications, ultra-high-resolution video streaming, and immersive extended reality (XR) experiences. However, THz waves also experience high free-space path loss and susceptibility to atmospheric absorption, which limits their propagation range. As a result, their use is most effective in short-range scenarios, such as indoor environments, dense urban networks, and device-to-device (D2D) communications, where line-of-sight (LoS) conditions can be maintained to maximize performance.

A cornerstone of the Network Everywhere vision is the creation of hyper-dense networks. Unlike previous generations of mobile networks, which relied on large, centralized macrocells to provide wide-area coverage, 6G networks will employ a vast number of small, low-power cells deployed across both indoor and outdoor environments. This includes femtocells, picocells, attocells, and even zeptocells, each covering extremely short ranges (sometimes as small as a few meters). These cells will be embedded into everyday infrastructure—walls, furniture, streetlights, and vehicles—creating a dense mesh of connectivity points that ensure no user is ever far from a network node. This high-density deployment enhances coverage, reduces latency, and supports ultra-high data rates. However, the increased number of transmitters operating at higher frequencies and shorter distances raises concerns about Specific Absorption Rate (SAR) and potential health effects due to increased electromagnetic radiation exposure. While regulatory bodies such as the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the Federal Communications Commission (FCC) set strict SAR limits to ensure user safety, further studies are required to evaluate the impact of ubiquitous small-cell deployments at higher frequencies. Recent research, such as [37], has investigated SAR levels in 5G millimeter-wave and THz communications, emphasizing the importance of power control, beamforming techniques, and regulatory oversight to mitigate potential risks.

By reducing the distance between users and access points, hyper-dense networks can achieve extremely high data rates with minimal latency. This densification also allows for the use of higher-frequency spectrum, such as millimeter-wave and terahertz bands, which offer vast bandwidth but are limited by short propagation ranges. In a hyper-dense environment, these higher-frequency signals can be effectively utilized, allowing 6G to support data-intensive applications like real-time Another critical enabler of Network Everywhere is the deployment of Distributed Antenna Systems (DAS) and innovations like radio-stripes. DAS involves spreading multiple antennas across a wide area, allowing

for improved signal distribution and network performance in high-density environments like stadiums, shopping malls, and urban centers. These systems can efficiently manage numerous simultaneous connections, ensuring that users experience consistent, high-quality service, even in crowded areas.

Radio-stripes represent an exciting development in antenna technology. First introduced by Ericsson in 2018 [38], radio-stripes are essentially long, flexible strips embedded with antenna elements that can be installed almost anywhere—on walls, ceilings, windows, or even roadways. These antenna strips are connected to the network through a shared bus that handles data transmission, synchronization, and power supply. Radio-stripes' flexible nature means they can be integrated into everyday objects and infrastructure, ensuring network coverage extends to every corner of the built environment. One of the key advantages of radio-stripes is their ability to reduce the physical distance between users and network nodes, leading to lower latency. Since signal propagation delay is directly proportional to distance, placing antenna elements closer to users reduces the time it takes for data to travel between the device and the network. Additionally, shorter distances result in higher signal strength and lower retransmission rates, further enhancing communication efficiency. This proximity-based advantage makes radio-stripes particularly well-suited for URLLC applications, such as industrial automation, smart cities, and real-time control systems.

Artificial Intelligence (AI) will play a fundamental role in 6G networks, particularly through the use of federated learning models. In a federated AI-based network, intelligence is distributed across multiple nodes, enabling real-time data analysis and decision-making without relying on centralized data centers. This approach will improve privacy, reduce latency, and optimize resource allocation across the network [39].

Federated learning allows devices at the edge of the network to collaborate in training machine learning models without sharing raw data. Instead, each device processes its local data and shares only model updates, which are then aggregated to improve the overall model's accuracy. This decentralized intelligence will be essential for managing the vast data generated by the Internet of Things (IoT), smart cities, and other connected environments. Additionally, integrating quantum computing into these networks will further enhance the capabilities of AI algorithms, allowing for faster and more efficient processing of complex tasks [40].

In 6G, AI will not only optimize network operations but also enhance user experiences by predicting user behavior, managing resources dynamically, and enabling new applications such as personalized virtual environments, autonomous vehicles, and advanced health monitoring systems [41].

3.5 Conclusions

In conclusion, the use cases envisioned for 6G networks paint a picture of a future where connectivity is seamless, intelligent, and omnipresent. By enabling unprecedented speed, capacity, and reliability, 6G will revolutionize how we live, work, and interact with technology. Applications such as holographic communications, remote healthcare, autonomous systems, and cooperative robotics will push the boundaries of innovation and create new opportunities for growth in critical sectors.

The deployment of 6G will also bring unique challenges, particularly in mobility management and resource allocation. However, technologies such as VSC and the introduction of advanced solutions like the HgNB-GW will play pivotal roles in addressing these challenges, ensuring that 6G networks can operate efficiently in the dynamic, high-density environments of the future.

Chapter 4

The Small Cell Integration into a 5G Network

This chapter addresses the integration of small cells in 5G networks, emphasizing the role of Multi-Radio Dual Connectivity (MR-DC) in achieving efficient interworking. Dual Connectivity (DC) was introduced in 3GPP's LTE Release 12 to enhance data throughput by enabling User Equipment (UE) to connect to two base stations. With the evolution toward Non-Standalone (NSA) 5G deployments, DC has expanded to include interworking between LTE and 5G New Radio (NR), known as Multi-Radio Dual Connectivity (MR-DC). This advancement supports several configurations in 4G and 5G cores, paving the way for improved network performance, higher data rates, and enhanced connectivity in dense urban areas and heterogeneous network environments.

MR-DC's architecture involves a primary Master Node (MN) for signaling and a Secondary Node (SN) for additional data transmission, effectively separating the control and user planes to optimize network load and user experience. In MR-DC configurations linked to a 5G core (5GC), the Access and Mobility Management Function (AMF) manages mobility and connection control, supporting seamless handovers and robust connectivity. This dual connectivity approach, integrating NR-NR or LTE-NR links, is foundational in supporting the future demands of Standalone (SA) 5G networks, ensuring consistent, high-capacity performance across increasingly complex network topologies.

Thanks to this configuration based on the 3GPP standard, the Small Cell (SC), acting as an SN, can be integrated into pre-existing cellular networks, enabling a more efficient signaling overhead reduction for the SC via gateways. This novel approach, proposed in this thesis, is the subject of analysis in this chapter.

4.1 Multi-Radio Dual Connectivity for 5G Small Cells Interworking

4.1.1 Deployment, Principles, and Architecture

DC was initially introduced in Release 12 of the 3GPP LTE specifications to enable a UE to connect to two base stations simultaneously. This feature, particularly advantageous in heterogeneous network deployments, allowed for increased data throughput and robust connectivity by utilizing two Radio Frequency (RF) interfaces. While initially designed for LTE networks, the advent of 5G and the need for Non Standalone (NSA) 5G deployments have expanded the role of Dual Connectivity (DC). In Release 15, the concept evolved into Multi-RAT Dual Connectivity (MR-DC), which extends dual connectivity across multiple radio technologies, allowing 5G New Radio (NR) and LTE to coexist in a network connected to either a 4G core network or a 5G core network. In this section, we focus on the development of DC and MR-DC, particularly their implementation in 5G, highlighting the key advancements and challenges.

The initial purpose of DC in Release 12 was to enhance heterogeneous LTE deployments, primarily by connecting a UE to two base stations, an Master Node (MN) for signaling and a Secondary Node (SN) for data transmission. This setup allowed UEs to benefit from throughput aggregation while decoupling control and user planes, thus optimizing network performance and load balancing. The bearer split in downlink introduced at this stage enabled efficient data flow management through two independent instances of Medium Access Control (MAC) and Radio Link Control (RLC) at the MN and SN, respectively [42].

However, some limitations of Release 12, such as incomplete support for multi-vendor deployments and limited uplink bearer capabilities, were addressed in Release 13. The uplink bearer split allowed the UE to use parallel MAC and RLC streams, which improved uplink efficiency and lowered power consumption. These enhancements contributed to more robust dual connectivity mobility and increased flexibility for heterogeneous networks [43].

The 5G NR technology development introduced the MR-DC framework in Release 15, which expanded the dual connectivity concept to integrate NR and LTE. This MR-DC framework enabled a UE to connect to an LTE eNodeB (eNB) and a 5G gNodeB (gNB) simultaneously, allowing operators to deploy 5G NR cells while still utilizing their existing 4G core networks. MR-DC offers several advantages, including increased data rates, enhanced mobility, and improved spectral efficiency [44].

The MR-DC framework also lays the groundwork for future Standalone (SA) 5G deployments, where both NR and LTE nodes will be connected to the 5G core network (5GC). In NSA 5G deployments, the LTE eNB acts as

the MN, while the NR gNB functions as the SN, managing data transmission in the downlink and uplink [45].

Name of MR-DC scheme	Core network	Main node	Secondary node	Interface with nodes	Interface with CN
EN-DC	EPC	eNB	gNB ->| en-gNB	X2	S1
NGEN-DC	5GC	eNB ->| ng-eNB	gNB	Xn	NG
NE-DC	5GC	gNB	eNB ->| ng-eNB	Xn	NG

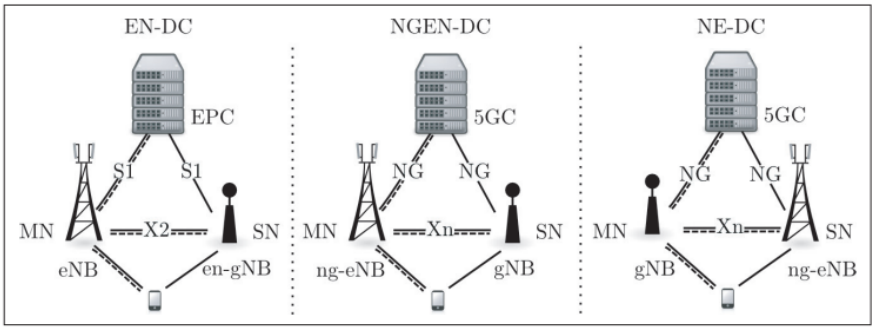

Figure 4.1: MR-DC network interfaces and architecture for the three standardized schemes

Figure 4.1 shows the architecture and network interfaces for the three MR-DC schemes described in the standard encompassing two different technologies. Dashed lines in the diagram represent control plane interfaces responsible for managing signaling and control information. On the other hand, continuous lines denote user plane interfaces, which handle the actual data transmission between nodes. It is important to note that, in all scenarios, the SN does not manage direct signaling with the end user. Instead, there is flexibility in how data is routed to the SN.

Data may either be routed through the master node MN before reaching the SN or be delivered directly from the core network to the SN. In the former case, where the data flows through the MN, this is referred to as an "MN-terminated bearer." Conversely, when the data is routed directly to the SN, the term "SN-terminated bearer" is used.

Furthermore, in MR-DC configurations involving the 5G Core (5GC), specifically in the NGEN-DC and NE-DC schemes, the core network entity responsible for handling signaling procedures is the Access and Management Function (AMF). The AMF oversees mobility management and connection control tasks, ensuring seamless handovers and connection setups.

For completeness, it is worth highlighting that the 3GPP standard also includes an NR-NR dual connectivity MR-DC scenario. In this setup, two NR nodes operate simultaneously, connected to a 5GC, allowing dual transmission to enhance throughput and improve service reliability. This configuration further extends the flexibility of MR-DC to support advanced deployments, ensuring robust connectivity across heterogeneous networks.

4.1.2 Protocol Stack and Bearer Management

In MR-DC, introduced in 3GPP Release 15, the control plane and user plane are split, each following distinct paths. From a control plane perspective, the X2 and Xn interfaces facilitate the coordination between the MN and the SN. All signaling from the core network is transmitted through the MN, ensuring that no direct control plane communication occurs between the SN and the end user unless it passes through the MN.

From the user plane perspective, MR-DC offers three distinct bearer configuration options:

- **Master Cell Group (MCG) bearers:** These bearers are served exclusively by the MN, which is responsible for handling both signaling and data transmission on the user plane.
- **Secondary Cell Group (SCG) bearers:** In this configuration, the SN serves the bearers on the radio interface, meaning the SN handles data transmission while signaling still passes through the MN.
- **Split bearers:** These bearers utilize radio resources from both the MN and the SN. In cases where split bearers are in use, data is transmitted after the Packet Data Convergence Protocol (PDCP) layer, routed to either the SN or MN via the X2 or Xn user plane interface, depending on the specific MR-DC scheme.

For added flexibility and enhanced mobility, MR-DC allows downlink bearers to reach the MN or SN directly from the core network, even if those nodes are not actively serving the bearers. In cases where the downlink bearers traverse the core network to reach the SN, the X2 or Xn user plane interfaces are established to ensure proper data transfer. This also holds for scenarios where split bearers are employed, further reinforcing the flexibility of the MR-DC architecture.

The protocol stacks used by the MN and SN in the various MR-DC schemes are illustrated in Figure 4.2. For simplicity, the EN-DC scheme is depicted with an LTE evolved NodeB (eNB) acting as the MN and an NR Next Generation Node B (gNB) as the SN. In this case, MCG bearers and split bearers are assumed to be processed by the MN, while SCG and split bearers are handled by the SN .

In cases where MCG bearers are served by the SN (e.g., NR bearers in NE-DC or NGEN-DC), the PDCPlayer is responsible for processing the bearer traffic before transferring it between the MN and SN using the X2 or Xn interfaces. When a split bearer is in use, the data is received at the MN, processed by the NR PDCP layer, and then distributed between the MN's and SN's RLC instances. If the bearer is SN-terminated, the distribution is handled by thePDCP layer at the SN. Upon receiving the data, the UE will use a single NR PDCP entity to reassemble the Packet Data Unit (PDU), ensuring correct data ordering across the different radio paths.

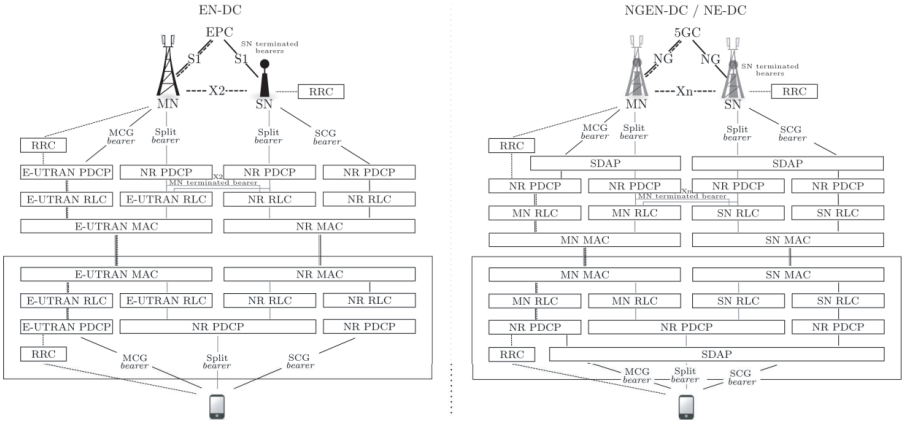

Figure 4.2: MR-DC network interfaces and architecture for the three standardized schemes

From the control plane's viewpoint, both the MN and SN have their own Radio Resource Configuration (RRC) entities. The MN, which is typically an LTE eNB or NR gNB, depending on the deployment scenario, is responsible for forwarding signaling messages from the SN to the User Equipment (UE). For example, RRC messages generated by the SN are transmitted via the MN through the MCG bearer. Additionally, the MN may combine its own RRC messages with those of the SN to provide unified signaling to the UE.

The MN typically maintains two Signalling Radio Bearer (SRB)s for control messages: SRB1, used for initial connection setup, and SRB2, employed for subsequent signaling procedures. In scenarios where the SN is an NR gNB, an additional SRB3 can be established directly between the SN and the UE to reduce signaling latency, particularly for Channel State Information (CSI) reporting. SRB3 may also carry SN-initiated RRC reconfiguration messages, although MN RRC messages are not mapped to this bearer.

The 3GPP standard also supports an NR-NR Dual Connectivity (NR-DC) configuration, where two NR nodes (gNB) are connected to the 5GC to enable dual transmission. In NR-DC, the master and secondary nodes are both gNB, allowing for increased throughput and reliability by utilizing NR radio resources on both the control and user planes. The NR-DC configuration provides enhanced flexibility for operators to manage user mobility and load balancing across the network, particularly in dense urban deployments where 5G coverage is critical.

In summary, MR-DC offers a highly flexible and efficient architecture for dual connectivity, allowing for optimized use of LTE and NR resources across different deployment scenarios. Whether through MCG, SCG, or split bearers, the integration of the control and user planes across the MN and SN ensures

seamless operation, with the ability to handle data and signaling efficiently for both 4G and 5G networks.

4.1.3 Operational Aspects

The 3GPP standard defines a comprehensive set of procedures related to MR-DC, covering node management, mobility, and signaling transfer. In all cases, the specifications differentiate whether the MR-DC is performed with the Evolved Packet Network (EPC) (EN-DC) or with the 5GC (NGEN-DC and NE-DC).

Concerning SN management, three key procedures are identified:

- **SN Addition**: This procedure establishes the MR-DC configuration for a UE by setting up its context and providing resources in the SN.
- **SN Modification**: This allows for the modification, establishment, or release of bearer contexts, as well as the adjustment of other properties of the UE context within the same SN.
- **SN Release**: This procedure releases the UE context in the SN.

The last two procedures (SN Modification and SN Release) can be initiated either by the MN or the SN.

Regarding mobility management, the standard defines four possible scenarios, as depicted in 4.3:

- **SN Change**: This procedure, which can be initiated by either the MN or SN, involves changing the SN while the MN remains the same.
- **Inter-MN Handover**: In this case, the UE transfers from one MN to another, while maintaining the MR-DC configuration.
- **MN to eNB/gNB Change**: Mobility results in the UE transitioning to a new MR-DC configuration while simultaneously changing its serving node.
- **eNB/gNB to MN Change**: The UE moves from a source cell to a target MN, which adds an SN during the handover.

Figure 4.3 illustrates an example where a user moves through different MN and SN, triggering various handover events.

Additionally, Figure 4.4 presents a simplified signaling flow for the SN Change procedure in the EN-DC scheme when the MN initiates the handover.

The following steps describe the SN Change procedure in more detail:

1. Upon receiving measurement reports that indicate the need for an SN change, the MN requests the target SN (Target SN (T-SN)) to allocate resources for the UE. This request is sent using an Source gNB (SgNB) Addition Request message.

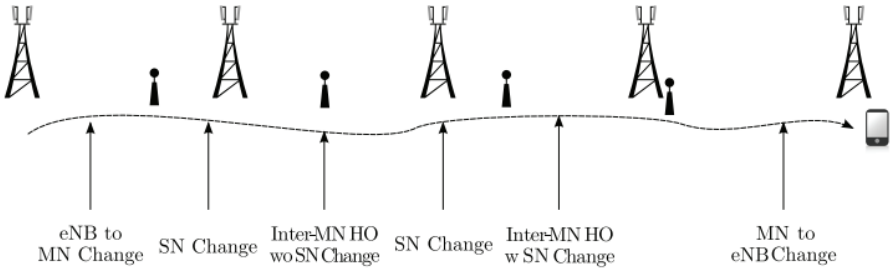

Figure 4.3: Four possible cases of MR-DC mobility

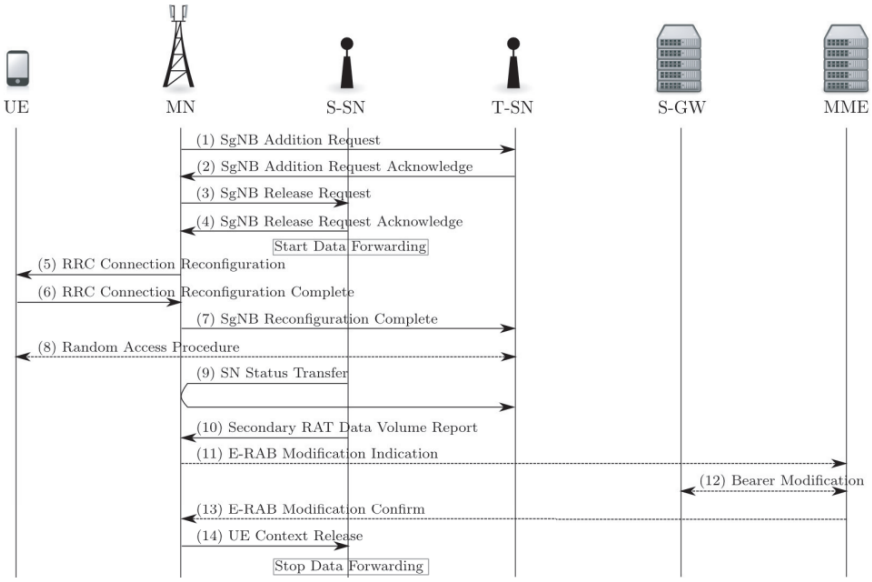

Figure 4.4: SN Change procedure initiated by the MN

2. The SgNB responds by confirming the availability of resources or denying the request, depending on its capacity.

3. If the T-SN admits the UE, the MN instructs the source SN (Source SN (S-SN)) to release its resources via an SgNB Release Request message, which the S-SN acknowledges.

4. The MN then sends an RRC Connection Reconfiguration message to the UE, including the necessary configuration for the T-SN. The UE responds with an RRC Connection Reconfiguration Complete message, which also contains the encoded NR RRC response for the T-SN.

5. The MN sends an SgNB Reconfiguration Complete message to the T-SN, after which the UE initiates the random access procedure to synchronize with the T-SN.

6. The S-SN transfers the UE status and a Data Volume Report to the T-SN via the MN, ensuring continuity in the UE's data connection.

7. If there are S-SN-terminated bearers, the MN starts the path update procedure with the EPC, and subsequently informs the S-SN about the UE context release.

Figure 4.4 does not represent the potential data forwarding between the S-SN and T-SN via the MN, but this can occur depending on the specific configuration, particularly when SN-terminated bearers are involved.

4.1.4 New Radio Small Cell Integration with DC Solution

Today's wireless networks primarily rely on high-powered macro cell towers to transmit signals across large distances. However, the deployment of SC has not yet reached the anticipated penetration levels. This is likely to change with the expansion of Fifth Generation (5G) into higher-frequency bands, particularly in the millimeter-wave spectrum. Due to the limited propagation of millimeter waves, which are highly susceptible to obstacles, a user moving behind an object could easily experience a connection drop. To address this issue, ultra-dense networks (UDNs) utilizing a vast number of low-power SCs deployed near end-users are expected to guarantee more stable connections by maintaining near-continuous line-of-sight (LoS) conditions [46].

While macrocells will continue to provide wide-area coverage to ensure service continuity during mobility, SCs will offer high data throughput within smaller coverage areas. Under the MR-DC framework, it is logical to designate the macrocell as the MN and the SC as the SN.

Operators must utilize small cell controllers to manage this large number of SCs while maintaining operational efficiency and keeping management costs reasonable. In LTE, this role is fulfilled by the home eNB gateway (Home

eNB Gateway (HeNB-GW)). Although a similar entity for NR has not yet been standardized, the current trend suggests that the 5G equivalent of the HeNB-GW will be based on cloud-edge computing.

Figure 4.5 illustrates the proposed architecture for integrating SCs into a cloud-edge network. This architecture leverages a cluster of computers running a virtual network function management system, such as OpenStack or VMware vCloud. A SC controller operates within a Virtual Machine (VM) on this cluster, interfacing with both the core network and the radio units, granting it a comprehensive view of the network's status. To efficiently manage a large number of VMs, a type-1 hypervisor (such as KVM or VMware vSphere) is recommended, as it enables multiple controllers to run in parallel. The SC controller's functionality can be dynamically adapted to changes in the MR-DC standard, and its capacity can be adjusted by the hypervisor, scaling resources like computing, networking, or storage as the number of managed SCs increases.

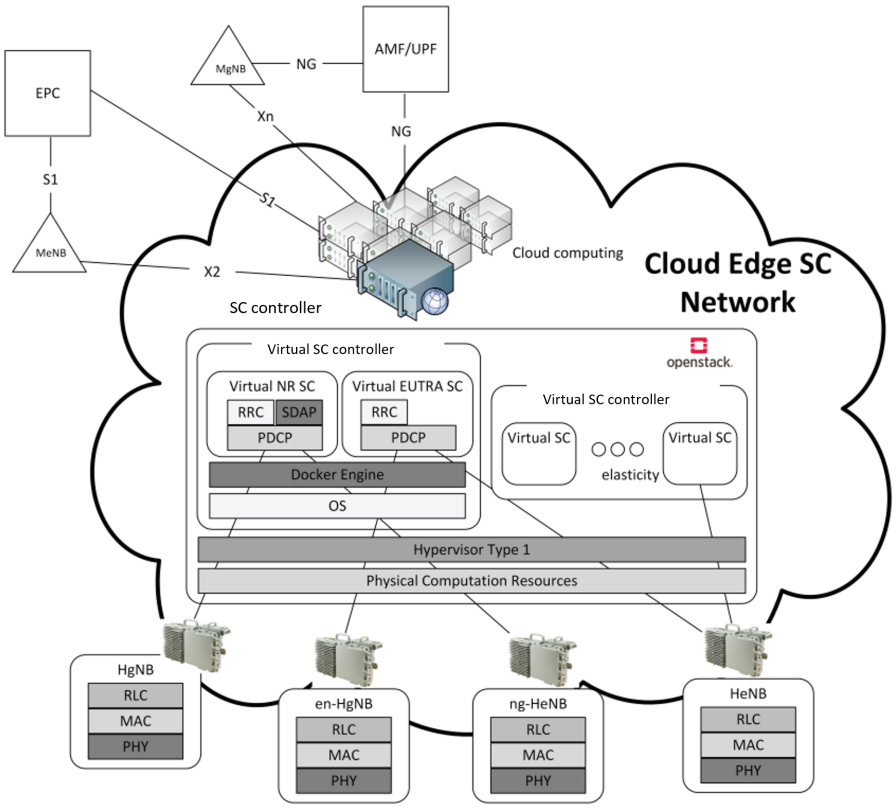

Figure 4.5: Architecture of the cloud edge SC controller and the use of dockers

From the perspective of the architecture in Figure 4.5, the SC controller manages all required interfaces for MR-DC schemes. To the core network and other MNs, the SDC acts as the SN and is connected via X2 and Xn interfaces to potential MNs (e.g., Master eNB (MeNB) and Master gNB (MgNB)). The SC controller oversees "light SCs," which are SCs that execute only lower-layer protocols (such as PHY, MAC, and RLC), while higher-layer protocols, including RRC and PDCP, are managed by the SC controller.

The light SCs broadcast their channels, allowing the UE to send measurement reports to the MN, which then determines whether an SC should be included in an MR-DC bearer. Since the MN is connected to the SDC, any requests for SC additions or modifications are processed by the SDC, which can instantiate virtual SCs to connect with the MN.

Given the need for rapid responses when including SCs in MR-DC configurations, traditional VM-based technology is not ideal due to the overhead of launching a full operating system. Instead, container-based technologies, such as Docker, are more suitable. Containers allow multiple virtual SCs to run on the same system, significantly reducing virtualization overhead and improving efficiency and responsiveness.

The primary advantage of this solution is that the SDC can dynamically adjust the upper-layer protocols of the SCs to support both Fourth Generation (4G) and 5G networks. Additionally, the SDC can enable legacy Home eNB (HeNB)s to participate in EN-DC without requiring software updates on the SC. This simplifies the implementation of SCs, which only need to manage lower-layer protocols, while the SDC handles the complexities of MR-DC integration.

This architecture can be extended through cloudification, moving additional protocol stack entities from the SCs to the SDC, a concept often referred to as fog computing. In a full fog computing scenario, SCs would operate as radio units executing only physical layer procedures. Offloading functions to the cloud would result in lighter SCs with lower latency due to several key architectural advantages. Traditionally, SCs handle both lower-layer (PHY, MAC, RLC) and higher-layer (RRC, PDCP) protocols, requiring local processing power and increasing end-to-end latency due to hardware limitations and processing overhead. However, by migrating higher-layer functions to the cloud-based SC controller, SCs are relieved of complex control and signaling tasks, allowing them to focus solely on low-latency, time-sensitive operations at the physical and MAC layers.

This latency reduction is primarily achieved through edge cloud deployment, also known as fog computing, where processing is offloaded to network-edge servers rather than distant centralized cloud data centers. Unlike conventional cloud computing, which may introduce additional transmission delays due to long-distance data travel, fog computing ensures that the SDC is geographically close to the SCs, reducing backhaul congestion and enabling faster decision-making. By processing MR-DC signaling, network coordination, and dynamic SCs instantiation at the SDC, the system avoids direct interactions

with the core network for every SC operation, significantly lowering the overall latency.

Furthermore, this architecture leverages container-based virtualization (e.g., Docker) instead of traditional virtual machines (VMs). VM-based virtualization often introduces higher startup overhead, as each instance requires launching a full operating system. In contrast, containers allow lightweight, rapid deployment of virtual small cells, ensuring near-instantaneous response times when adapting to network conditions. This ability to dynamically instantiate virtual SCs helps maintain seamless mobility management and optimized handover performance, both of which are critical in MR-DC configurations.

Additionally, since radio access decisions and higher-layer signaling are centralized at the SDC, the network can intelligently manage resources, avoid redundant protocol overhead, and minimize latency spikes caused by local processing constraints at individual SCs. This not only improves the efficiency of MR-DC bearer management but also enhances overall network responsiveness, making it particularly well-suited for URLLC applications.

Thus, contrary to the assumption that cloud offloading increases latency, this architecture actually reduces it by optimizing processing distribution, leveraging fog computing, and using lightweight container-based virtualization to ensure faster reaction times, improved scalability, and enhanced real-time performance. In this sence, the innovation of this chapter lies in integrating of MR-DC signaling management within the SC controller.

With the growing demand for seamless interworking between wireless and wireline networks, the 3GPP has advanced Wireless Wireline Convergence (WWC) by introducing support for 5G Residential Gateways (5G-RGs). This development extends the MR-DC paradigm beyond just radio access networks, integrating fixed-line services into the 5G ecosystem. A 5G-RG is inherently multi-access, capable of handling multiple sessions and Protocol Data Unit (PDU) session types. It facilitates persistent management and session processes, genuine multi-access functionality through Access Traffic Steering, Switching, and Splitting (ATSSS), and utilizes Universal Subscriber Identity Module (USIM) authentication to enhance device security.

By steering traffic between access technologies based on performance metrics such as latency and throughput, the 5G-RG can prevent session failures preemptively. This focus on fundamental Quality of Service (QoS) ensures that the 5G-RG prioritizes entry points into fixed or mobile connections, providing operators with increased reliability and accessibility. Moreover, it offers the flexibility to leverage reputable third-party applications for interacting with the 5G network, thereby extending the capabilities and reach of the 5G-RG.

As operators aim to enhance customer and industry satisfaction, the integration of 5G-RGs into the broader 5G network has become crucial. This shift also aligns with ongoing enhancements in MR-DC, which could eventually support multi-radio interconnections beyond LTE and NR, potentially including IEEE 802.11 networks. The ability to simultaneously manage multiple radio access technologies within a unified architecture leveraging both cloud-based

SC controllers and 5G-RGs can significantly improve network efficiency, reduce operational costs, and enhance service continuity for users.

In conclusion, while the proposed cloud-edge SC controller architecture has demonstrated feasibility and strong performance (as depicted in Figure 4.5), additional research is needed to explore alternative protocol split strategies. The introduction of 5G-RGs as part of 3GPP's WWC efforts marks a significant step forward in convergence, but further development is required to synchronize layers efficiently, ensuring that both wireless and wireline components of the network are seamlessly integrated for optimal performance.

4.2 Implementation of Network Slicing for the 5G Small Cells Integration

4.2.1 Introduction

In recent years, significant technological alternatives have been explored to optimize the configuration of network slices in 5G networks. One promising approach is the combined use of VM and containers, which provide a flexible and scalable solution for network virtualization. This thesis builds upon the experience gained from the 5G-ESSENCE project [47], presenting a comprehensive guide to configuring network slices using these virtualization technologies.

Network slicing is a fundamental concept in the 5GC architecture, enabled by advanced virtualization technologies such as Network Functions Virtualization (NFV) and Software-Defined Networking (SDN). It allows operators to create isolated virtual networks over a shared physical infrastructure, thereby tailoring network resources to meet the diverse requirements of different services, such as enhanced mobile broadband Enhanced Mobile Broadband (eMBB) and ultra-reliable low-latency communication Ultra-Reliable and Low Latency Communications (URLLC).

On December 21, 2017, Third Generation Partnership Project (3GPP) announced the completion of the first phase of the 5G standard, marking a critical milestone in the evolution of mobile networks. This phase, formalized in 3GPP Release 15, defines the foundational aspects of NR technology and establishes the framework for the future of 5G. Key features of this initial release include the use of millimeter-wave (mmWave) frequencies, advanced Multiple-Input Multiple-Output (MIMO) techniques, and the introduction of network slicing for service isolation. Additionally, 5G ensures joint operation and backward compatibility with 4G networks.

While the completion of Release 15 lays the groundwork for 5G, further developments are already underway. In June 2018, 3GPP defined study items for Release 16, which focuses on extending the capabilities of 5G. Key areas include Vehicle-to-anything (V2X) support for autonomous driving, enhanced MIMO technologies for massive MIMO, and the integration of unlicensed spectrum. Other focus areas include the convergence of satellite networks with

terrestrial networks and the support for factory automation and other vertical use cases.

A crucial element in realizing the full potential of 5G is the deployment of SCs, which are essential for providing the high capacity and low latency required by advanced 5G services. The deployment of SCs is closely linked to network slicing, enabling operators to dynamically allocate network resources to different services through virtualization techniques such as NFV and SDN [48] [49].

The 5G-ESSENCE project [47], a European research initiative, is focused on enabling an efficient deployment of SCs in 5G networks. Its goal is to integrate multiple Radio Access Technologies (RAT) into a single virtualized edge infrastructure that supports multi-tenancy and network slicing. The project emphasizes the seamless management of diverse radio technologies to create a unified and flexible 5G network.

A core element of the 5G-ESSENCE architecture is the mixed use of virtual machines, which function as Infrastructure-as-a-Service (IaaS), and containers, which serve as Platfrom as a Service (PaaS). This hybrid model allows for scalable and efficient management of network resources. Virtual machines provide isolated environments for running network functions, while containers enable rapid deployment of lightweight services, making them ideal for dynamic environments such as SC deployments.

The architecture proposed by 5G-ESSENCE is based on cloud-edge computing, where network functions are virtualized and deployed across the network's edge. This setup ensures efficient orchestration of virtual network functions (VNFs), allowing SCs to operate as part of a larger unified network, providing high throughput and low latency.

In the 5G-ESSENCE architecture, virtual machines play a critical role in providing IaaS for 5G network functions. By virtualizing physical hardware, VMs enable network operators to run multiple instances of network functions on a shared infrastructure, thereby improving resource utilization and reducing the need for dedicated hardware.

The deployment of VMs in 5G networks is typically managed through cloud orchestration platforms such as OpenStack, which provides tools for managing compute, storage, and networking resources in distributed environments. OpenStack allows operators to dynamically allocate resources to different network slices, ensuring that service-level agreements (SLAs) are met for each slice. This feature is essential in the context of 5G.

One of the key advantages of using VMs in 5G networks is the strong isolation they provide between different network functions, ensuring that the failure of one function does not affect the performance of others. VMs also offer mature security features, making them ideal for multi-tenant environments where critical infrastructure protection is paramount.

In addition to VMs, containers have emerged as a key technology for deploying network functions in 5G networks, particularly in PaaS environments. Containers are lightweight, share the host operating system kernel, and of-

fer faster deployment times compared to VMs, making them ideal for scaling network functions dynamically.

Docker, a widely adopted container platform, is critical in the 5G-ESSENCE architecture. Using containers, network operators can deploy services rapidly, reducing resource overhead while maintaining the high scalability required by SCs. In the hybrid architecture proposed by 5G-ESSENCE, containers can be deployed alongside VMs on the same physical infrastructure, providing flexibility in resource management.

The key benefit of containers is their ability to scale services dynamically based on real-time network conditions. This is particularly useful in SC deployments, where the network must adapt quickly to changes in user demand and service requirements.

4.2.2 Network Virtualization and Slicing

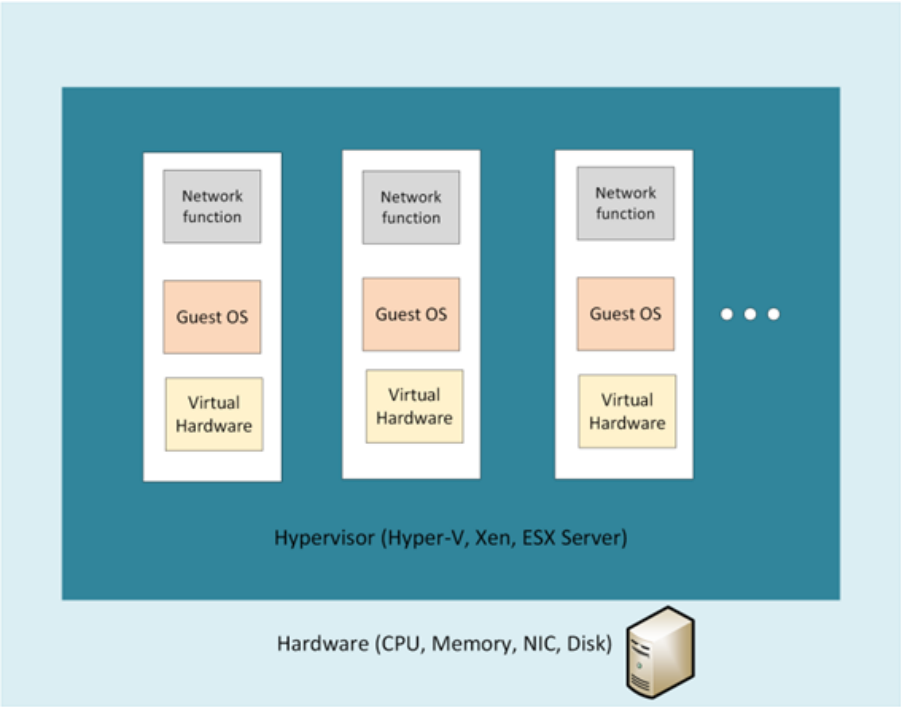

Figure 4.6: Architecture of Virtual Machines running VNFs on the same hardware. Each VM operates independently with its OS

Communication networks have traditionally relied on dedicated hardware, which creates challenges in flexibility, scalability, and cost. Introducing new services or adapting to evolving requirements has often been a slow process due to the need for hardware upgrades. Virtualization solves these issues by decoupling network functions from physical hardware, enabling dynamic resource allocation and flexible service provisioning.

Network virtualization is built on two key technologies: NFV and SDN. NFV allows network functions to run as software on general-purpose hardware rather than on specialized hardware devices. Virtual Network Function (VNF) are deployed in VMs or containers, providing significant flexibility in how and where network services are executed. SDN complements NFV by enabling centralized control over the network, allowing for dynamic configuration and optimization of resources based on real-time needs.

In a virtualized network, hardware resources must be allocated efficiently to ensure high and predictable performance, particularly for services with strict Service Level Agreement (SLA)s. The European 5G-ESSENCE project pro-

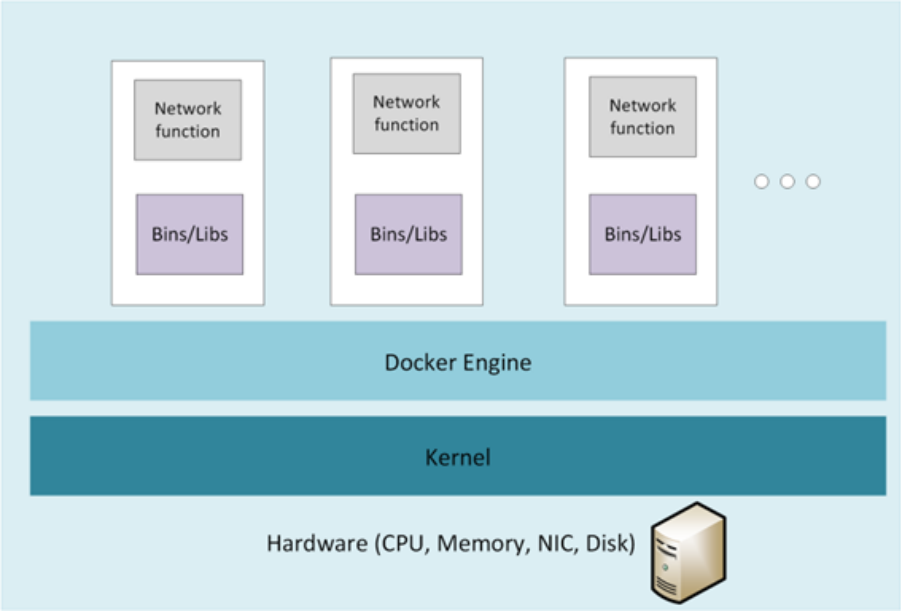

Figure 4.7: Architecture of Containers running VNFs, sharing the OS kernel on the same hardware

posed a scalable 5G solution based on edge cloud computing and Small-Cell-as-a-Service (SCaaS). This architecture emphasizes using a SC controller to manage the interconnection between VNFs and infrastructure, optimizing resource allocation across the network.

A key consideration in network virtualization is the choice between VMs and containers. The primary distinction lies in the level of abstraction: VMs abstract the hardware layer and run separate operating systems for each instance. In contrast, containers abstract the OS layer, sharing the same kernel across multiple applications.

Containers are more lightweight than VMs, enabling faster deployment and lower resource consumption, which is especially beneficial for latency-sensitive applications in 5G networks. However, containers offer less isolation than VMs, as they share the host OS kernel, making them less secure in multi-tenant environments where strict isolation is required. VMs, in contrast, provide better isolation by running separate OS instances, making them more suitable for environments that demand strong security guarantees.

Figures 4.6 and 4.7 illustrate the architectures of VMs and containers. VMs run independent OS instances, while containers share the host OS kernel. Containers provide higher density and faster deployment, whereas VMs ensure stronger isolation.

Network virtualization, through NFV and SDN, is essential for the flexibility and scalability required by 5G networks. The choice between VMs, and containers depends on the specific use case, with containers offering better performance for high-density applications, while VMs provide greater security and isolation

4.2.3 Virtualization Solution for Small Cells

To support an open and multivendor virtualization framework, we propose a highly flexible heterogeneous architecture where containers run inside virtual machines (VMs). This approach balances security, isolation, and performance while ensuring seamless compatibility across different infrastructures. By combining the benefits of both VMs and containers, we take advantage of the strong security guarantees and isolation mechanisms offered by VMs, while leveraging containers' lightweight, rapid deployment, and high resource efficiency.

Although running containers inside VMs introduces some additional hardware resource consumption compared to bare-metal containers, this trade-off is necessary for several reasons:

- **Security and Isolation**: VMs provide stronger isolation than standalone containers, making them a more secure choice for multi-tenant environments where different service providers or vendors may share the same infrastructure. *Mitigation:* Modern lightweight hypervisors (e.g., KVM, Firecracker, Kata Containers) help reduce performance overhead while maintaining security.

- **Interoperability and Multi-Vendor Compatibility**: Many network operators and service providers use a mix of legacy, virtualized, and cloud-native environments. Running containers inside VMs ensures that different vendor solutions can coexist without requiring deep modifications to existing infrastructure. *Mitigation:* This architecture ensures a seamless transition from traditional VM-based network functions VNFs to containerized network functions without compromising compatibility.

- **Optimized Resource Utilization for Edge and Cloud Deployments**: This architecture is infrastructure-agnostic, meaning it can be deployed in both centralized cloud environments and distributed edge networks. Edge computing benefits from this setup by offloading control functions to a centralized location while keeping low-latency functions at the edge. *Mitigation:* Efficient orchestration tools (e.g., **KubeVirt, OpenStack, Kubernetes**) ensure optimal resource allocation to balance performance and consumption.

- **Performance vs. Startup Time Trade-Off**: While VMs take longer to initialize compared to bare-metal containers, they provide more stability and control over resource allocation. Containers within VMs can still

start up almost instantly, reducing the impact of this limitation. *Mitigation:* Using snapshot-based VM booting, container preloading, and just-in-time instantiation helps optimize startup performance.

This virtualization approach provides an efficient, scalable, and secure solution for managing SCs in heterogeneous 5G and beyond networks. While it does introduce some hardware overhead, the benefits in security, flexibility, and interoperability make it a practical choice for multi-vendor, dynamic environments, ensuring seamless network function integration across cloud and edge infrastructures. Figure 4.8 illustrates the integration of VMs and con-

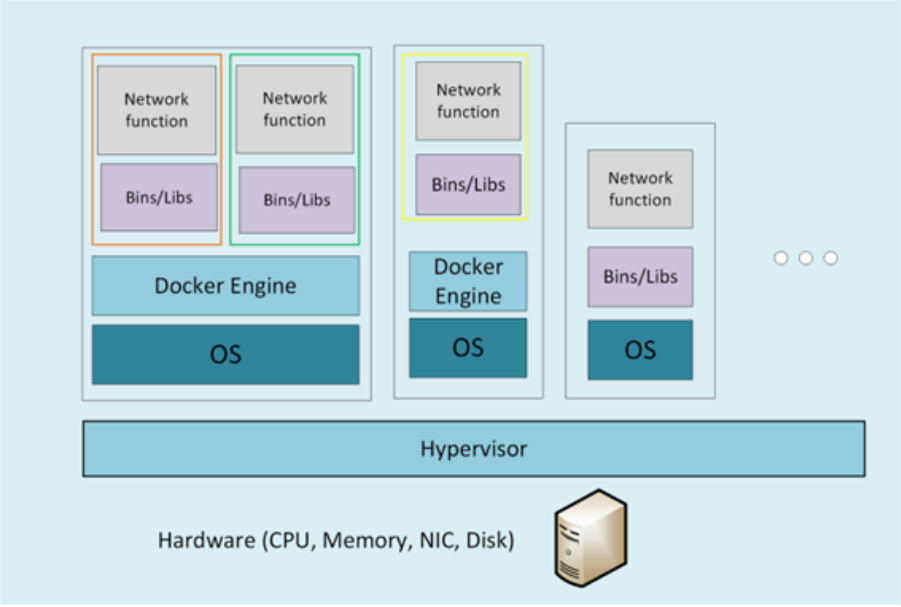

Figure 4.8: Architecture of Containers running VNFs, sharing the OS kernel on the same hardware

tainers. This setup makes communication between different services hosted on VMs and containers possible. For example, containers running applications can seamlessly communicate with a database hosted on a VM. This structure is advantageous for use cases like 5G end-to-end (E2E) slicing for mission-critical applications. In such scenarios, applications such as group communication (supporting one-to-one and one-to-many communications) require ultra-low latency. Deploying the VNFs inside a container minimizes overhead, while the use of VMs ensures security and isolation between tenants. This makes deploying containers within VMs an optimal solution.

4.3 Practical Deployment of a Network Slice

Figure 4.5 demonstrates the integration of this virtualization solution within the 5G ESSENCE architecture, where the SC controller operates inside a VM, and virtual small cells (vSCs) run as containers within each VM. This setup enables multi-tenancy, ensuring each tenant can manage an independent virtual **vSC!** (**vSC!**) controller with high isolation and security. The rapid deployment of vSCs within each SC controller enhances scalability and flexibility, making it an efficient solution for small cell virtualization in 5G networks. While the figure does not depict the split between the UP and CP, the architecture requires multiple interfaces to ensure seamless communication between the vSC controller, vSCs, physical SCs, and core networks such as the 5GC and EPC. The interface between the vSC controller and 5GC or EPC is essential for handling control and user plane traffic, using protocols such as NG (Next Generation, N2 for control signaling and N3 for user data) in 5G, S1 (S1-C for control and S1-U for data) in LTE, and Xn interfaces for inter-cell communication, while cloud-native systems may use REST (Representational State Transfer) or gRPC (gRPC Remote Procedure Call) APIs for network function orchestration.

The vSC controller communicates with vSCs primarily through software-defined networking (SDN) based-protocols like OpenFlow for dynamic network configuration, NETCONF (Network Configuration Protocol) or YANG (Yet Another Next Generation) for network function management, and gRPC or Kafka-based messaging for real-time coordination, ensuring efficient mobility management and resource allocation. The interface between vSCs and physical SCs is critical for radio resource management and can use protocols such as F1 (F1-C for control and F1-U for user data) in 5G, eCPRI (enhanced Common Public Radio Interface) for high-speed fronthaul transport in cloud radio access network (C-RAN) deployments, and O-RAN E2 interface for real-time RAN control and optimization. Communication between OpenStack and virtual network functions (VNFs), including vSCs and the vSDC, is handled through OpenStack APIs for provisioning, VXLAN (Virtual Extensible LAN) or GRE (Generic Routing Encapsulation) for overlay network creation, and storage interfaces like iSCSI (Internet Small Computer Systems Interface) and NFS (Network File System) for persistent storage solutions. This architecture provides a cloud-native, flexible, and programmable environment where SDN, network function virtualization (NFV), and OpenStack orchestration enable efficient resource allocation and dynamic scalability, making it a robust framework for 5G small cell deployment and network slicing.

OpenStack's storage system supports both **ephemeral** and **persistent** storage. Ephemeral storage is temporary and is deleted when an instance is terminated, while persistent storage remains intact across instance terminations. OpenStack refers to persistent storage as a **volume**, which can be used to launch an instance or attached to an existing instance for long-term data storage.

In OpenStack, volumes are managed by the **Cinder** service, which provides functionalities to create, modify, or delete volumes as needed. Additionally, the **Swift** service enables object storage support, allowing for scalable and reliable data storage solutions.

4.3.1 Software Defined Networking with Neutron

OpenStack integrates SDN through the **Neutron** service, which includes support for routing, firewalls, Domain Name Service (DNS), Dynamic Host Configuration Protocol (DHCP), load balancing, and Virtual Private Network (VPN) capabilities. Neutron enables the creation of tenant networks—isolated virtual networks that share the same physical infrastructure while maintaining strict traffic separation. Neutron achieves network isolation through various techniques, such as Virtual Local Area Network (VLAN)s, Virtual eXtensible Local Area Network (VXLAN)s, and Generic Routing Encapsulation (GRE) tunnels.

Once the isolation scheme is defined, Neutron allocates network resources according to the established configurations. For instance, a VLAN switch can be configured with specific VLAN ranges to enforce isolation. Neutron automatically assigns a unique VLAN to each newly created network, ensuring the networks remain isolated. Moreover, virtual routers can connect separate networks, allowing for inter-network communication. This architecture offers a complete abstraction layer, which enables virtual networks to be dynamically mapped onto physical network resources without security or address conflicts.

4.3.2 Multi-Tenancy in OpenStack

A core feature of OpenStack is its support for **multi-tenancy**, which allows multiple users or projects to share the same physical resources with full isolation between tenants. OpenStack's multi-tenancy model ensures that virtual resources are kept separate, even when hosted on shared infrastructure. This transparent separation allows cloud administrators to share physical resources efficiently while guaranteeing data and resource isolation for each tenant.

4.4 Installation

The first step to deploying OpenStack is setting up a dedicated server where all OpenStack services will run, referred to as the **controller node**. In this thesis, the **DevStack** deployment of OpenStack was chosen due to its simplicity and ease of installation. DevStack is a streamlined, full-featured version of OpenStack, providing a comprehensive OpenStack environment. However, DevStack is resource-intensive, making it preferable to install it on a dedicated or isolated VM.

For isolation purposes, DevStack was installed on a VM running on a personal computer. This approach isolates real hardware resources from potential issues encountered during installation, ensuring that any errors in the deployment process do not impact the host system.

4.4.1 Accessing the Horizon Dashboard

During the DevStack installation, an IP address and default administrator credentials are assigned to the server. The **Horizon** service is available upon successful installation, providing a web-based dashboard to manage OpenStack resources. The Horizon dashboard can be accessed via the following URL:

```
http://<Server IP Address>/dashboard/auth/login/
```

Upon accessing the Horizon dashboard, users can view the physical resources available in the network, including CPU, memory, and storage allocations, as well as the utilization of those resources by existing instances. Figure 4.9 shows an example view of the Horizon dashboard on a local PC with 4 CPUs, where two instances (*test1* and *test2*) have been created, each with 1 GB of ephemeral storage and 512 MB of RAM.

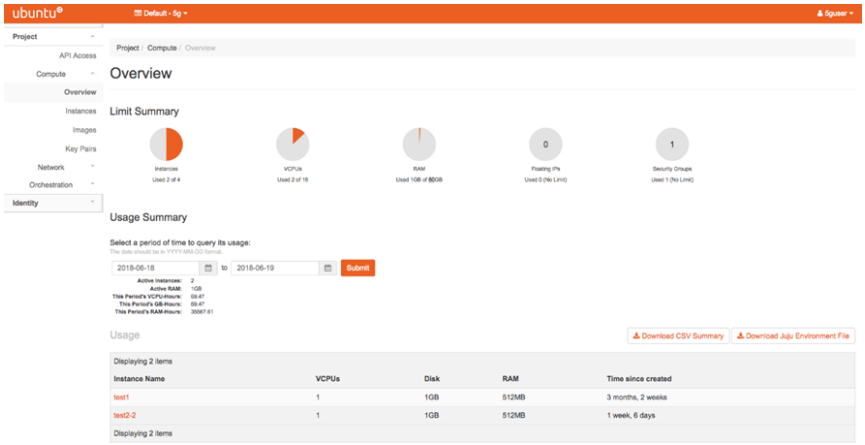

Figure 4.9: Initial view of the Horizon dashboard showing available physical resources

4.4.2 Creating and Managing Images in OpenStack

An **image** in OpenStack is a snapshot of a storage device that includes the operating system, applications, and configurations necessary to launch a virtual machine. After installing DevStack, a default image (typically Cirros) is available, with additional images accessible through the OpenStack repository. Images do not run independently; they serve as templates to create instances.

To create an image from an existing operating system configuration, the `diskimage-builder` tool can be used. For instance, after configuring an Ubuntu system with all required applications, `diskimage-builder` can generate an image file from this setup.

The following commands install `diskimage-builder` and create an Ubuntu image:

```
sudo apt install python-diskimage-builder
disk-image-create ubuntu VM
```

The output is a `.qcow2` file, which can be added to Horizon under the **Images** section. Once uploaded, the image becomes available for instance creation. Figure 4.10 illustrates adding an image to the repository.

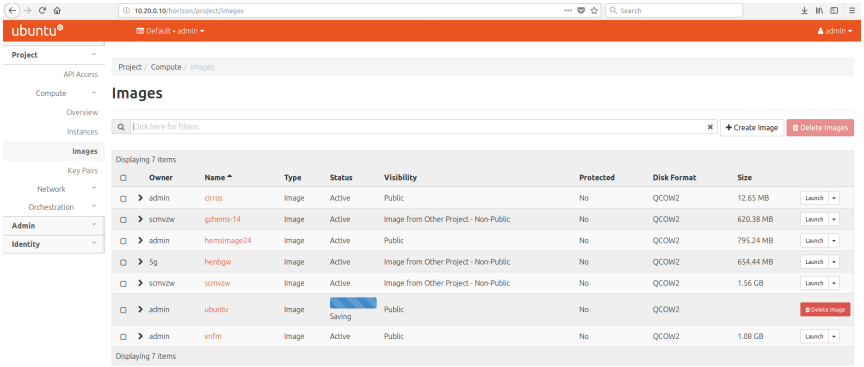

Figure 4.10: Adding a new Ubuntu image to the Horizon dashboard

4.4.3 Launching Instances and Configuring Flavors

An **instance** is a VM running in the OpenStack environment. Instances can be created from available images in the repository or custom images uploaded by the user. Each instance has a **flavor**, a predefined configuration specifying CPU, memory, and storage resources.

To launch an instance:

1. Select the desired image and, if needed, assign a persistent or ephemeral volume.

2. Choose an appropriate flavor, as shown in Figure 4.11. Each flavor specifies the instance's CPU, RAM, and disk size, ensuring sufficient resources for the selected image.

The system will generate an error if insufficient resources are assigned, such as allocating a VM with only 512 MB of RAM for an OS that requires 2 GB.

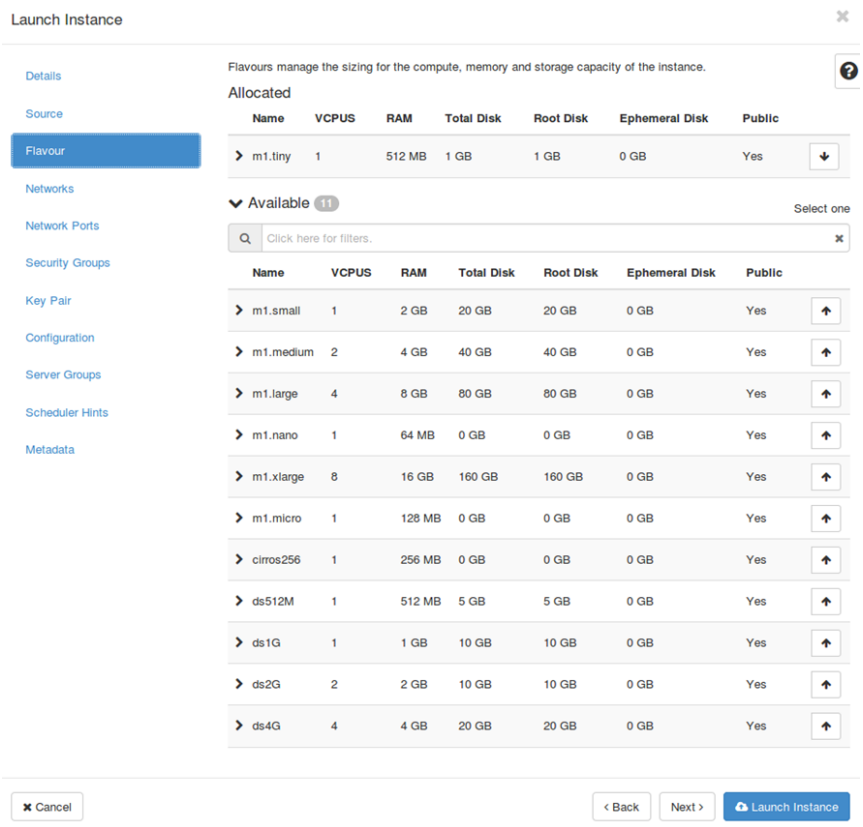

Figure 4.11: Flavor selection for a virtual machine in Horizon

4.4.4 Network Configuration and Instance Assignment

The final step in launching an instance involves configuring network connections. OpenStack allows VMs to connect to one or more virtual networks, enabling flexibility in network configuration. A **network slice** can be created by deploying multiple VMs, each connected to different subnets or network segments.

By following this methodology, an entire network slice can be simulated. For instance, some VMs can emulate base stations, others function as switching elements, and a designated VM serves as the internet gateway. The appropriate images for each entity are uploaded, and the connections are configured through the Horizon interface.

Next we describe the implementation of network slicing for 5G small cells using OpenStack. Two slicing methods are considered: **Tenant-Based Network Slicing**, ensuring complete isolation of resources, and **QoS-Based Net-**

work Slicing, which dynamically allocates resources based on network policies.

4.4.5 Tenant-Based Network Slicing

Tenant-based slicing provides strict isolation by assigning separate projects to different slices. Each tenant manages its own network, users, and resources independently. The steps to implement tenant-based slicing are:

- **Create separate projects**: Each slice is assigned a dedicated OpenStack project.
- **Assign users to projects**: Ensures that only authorized users access each slice.
- **Configure isolated networks**: Each tenant receives a private virtual network.
- **Set up routers for external connectivity**: Ensures slices can access external resources while maintaining isolation.

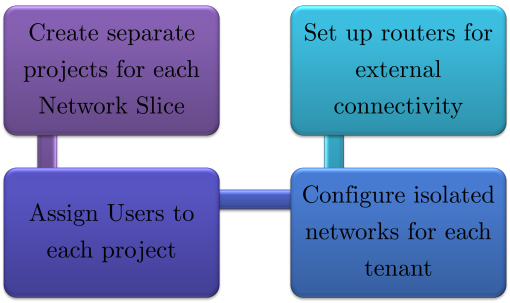

Figure 4.12: Process of setting up tenant-based network slicing in OpenStack

The process of implenetation follows the following steps:

Step 1: Create Separate Projects Each network slice is mapped to an OpenStack project:

```
openstack project create tenant1
openstack project create tenant2
```

Step 2: Assign Users to Projects Each user is associated with a specific tenant:

```
openstack user create --password mypassword user1 --project tenant1
openstack user create --password mypassword user2 --project tenant2
```

Step 3: Configure Isolated Networks Each project is assigned a private network:

```
openstack network create --project tenant1 slice1-private
openstack subnet create --network slice1-private--
subnet-range 10.1.1.0/24 slice1-subnet

openstack network create --project tenant2 slice2-private
openstack subnet create --network slice2-private --
subnet-range 10.2.2.0/24 slice2-subnet
```

Step 4: Set Up Routers Routers are added to provide external access:

```
openstack router create --project tenant1 slice1-router
openstack router create --project tenant2 slice2-router
```

Once these steps are completed, each tenant operates as an independent slice with strict isolation.

4.4.6 QoS-Based Network Slicing

QoS-based slicing enables multiple slices to share the same network infrastructure while enforcing bandwidth limits and prioritizing traffic types.

The QoS policies available in DevStack (Neutron) provide essential traffic management mechanisms for ensuring efficient resource allocation in virtualized network environments. These policies include Bandwidth Limits, which restrict the upload and download speeds of network traffic by defining a maximum allowable bandwidth in kbps. DSCP Marking is used to prioritize certain packets based on predefined classifications, ensuring that high-priority applications, such as real-time communications, receive better handling. The Minimum Bandwidth policy guarantees a baseline level of bandwidth allocation for specific traffic flows, preventing congestion-related degradation and ensuring service quality. Lastly, Packet Rate Limiting controls the number of packets transmitted per second (PPS), helping to regulate network load distribution and prevent excessive resource consumption by a single user or application. Collectively, these QoS policies optimize network slicing performance by balancing traffic priorities, enforcing service-level agreements (SLAs), and ensuring fair resource allocation in multi-tenant 5G small cell environments.

The key steps for implementing QoS-based slicing are:

- **Verify available QoS policies**: Ensure OpenStack Neutron supports required QoS extensions.
- **Create QoS policies**: Define bandwidth limits and traffic prioritization rules.

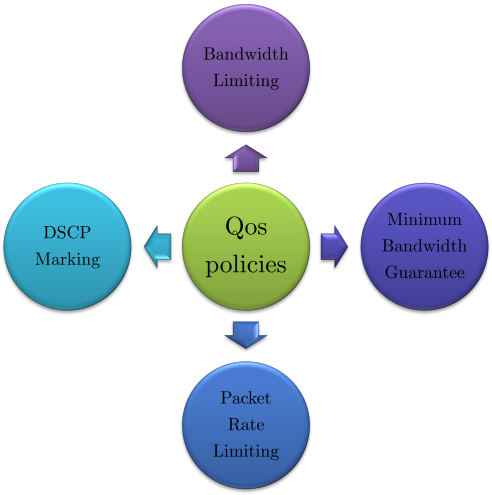

Figure 4.13: QoS Policies Overview

- **Attach QoS policies to networks**: Apply QoS rules to manage network traffic efficiently.

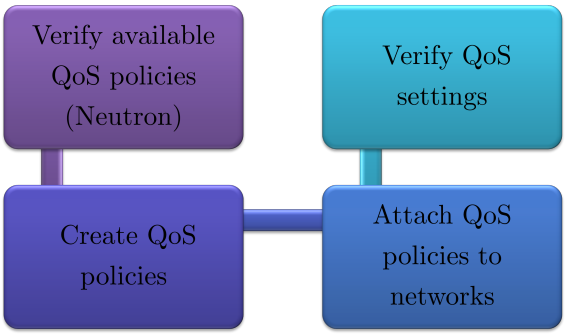

Figure 4.14: Process of setting up QoS-based network slicing in OpenStack

The implementation prcess folows the following steps:

Step 1: Verify Available QoS Policies List existing QoS policies:

```
openstack extension list --network | grep qos
```

Step 2: Create QoS Policies Define a QoS policy with bandwidth limits:

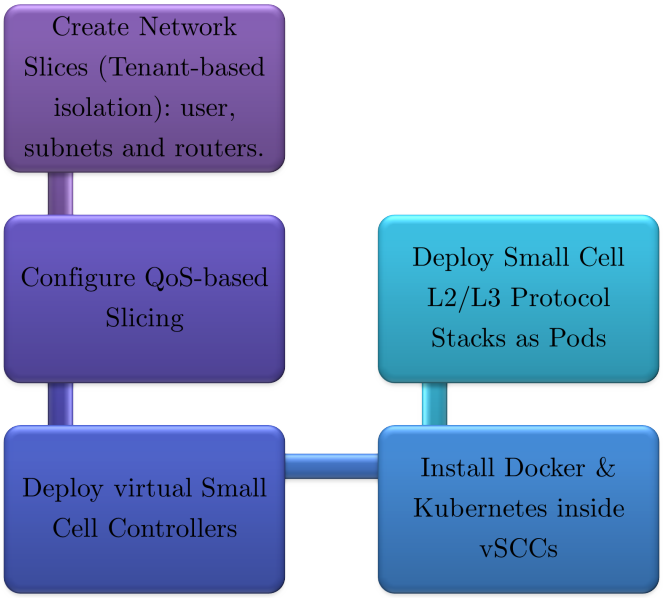

Figure 4.15: Overall network slicing implementation process

```
openstack network qos policy create qos-slice1

openstack network qos rule create --type bandwidth-limit --max-kbps

100000 --egress qos-slice1
```

Step 3: Attach QoS Policies to Networks Apply QoS rules to a specific network:

```
openstack network set --qos-policy qos-slice1 slice1-private
```

This setup ensures that slices can dynamically allocate bandwidth based on real-time needs while maintaining performance guarantees.

With these two slicing approaches, the implementation ensures flexibility in 5G small cell deployments. Tenant-based slicing provides strong isolation, while QoS-based slicing optimizes resource allocation dynamically.

4.5 Practical Deployment of Containers

Containers represent a lightweight alternative to traditional VM for deploying and running software. Unlike VMs, containers do not require a full operating system for each instance. Instead, they share the kernel of the host OS, which

significantly reduces overhead and improves performance. Containers package the application and its dependencies into a standardized software unit, allowing it to run consistently across different computing environments.

In this section, we will walk through the practical deployment of containers using Docker, a popular containerization platform. Docker enables developers to deploy applications in isolated containers, which ensures consistency, scalability, and ease of management.

4.5.1 Installation of Docker

Before deploying containers, Docker must be installed on the host machine. Docker is compatible with various operating systems, but we will focus on Ubuntu as the base OS for this thesis. To install Docker Community Edition (CE), which is a lighter version of the Docker package, the following commands need to be executed in the terminal:

```
sudo apt-get update
sudo apt-get install \
    apt-transport-https \
    ca-certificates \
    curl \
    software-properties-common
curl -fsSL https://download.docker.com/linux/ubuntu/gpg |
    ↪ sudo apt-key add -
sudo add-apt-repository \
   "deb [arch=amd64] https://download.docker.com/linux/
       ↪ ubuntu $(lsb_release -cs) stable"
sudo apt-get update
sudo apt-get install docker-ce docker-ce-cli containerd.io
```

Once Docker is installed, it can be managed and monitored through the dashboard. In this case, we will use Portainer, a web-based interface simplifying container management. The Portainer dashboard can be accessed by navigating to `127.0.0.1:9000` in a web browser.

Figure 4.16 illustrates the Portainer dashboard, where the administrator can monitor the containerized applications and available resources and perform various management tasks, such as loading images, configuring networks, and setting volumes for storage.

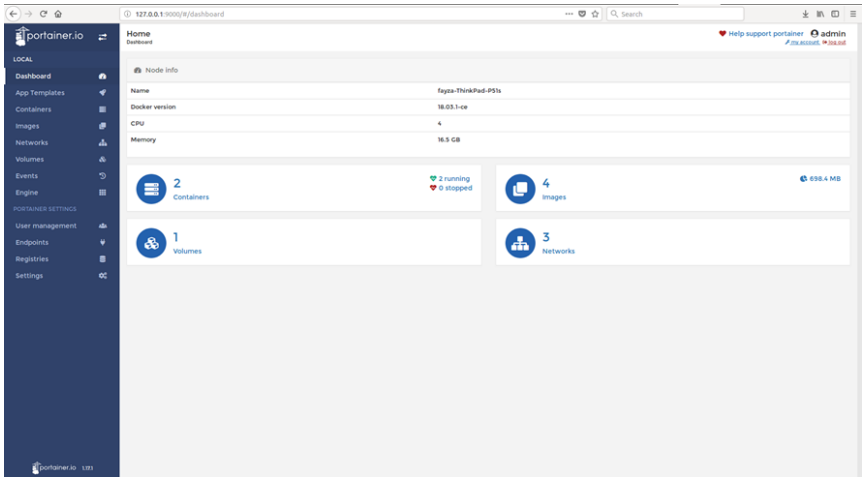

Figure 4.16: Docker Portainer Dashboard: Managing containers, networks, and storage

4.5.2 Managing Docker Images and Containers

One of the core functionalities of Docker is the ability to create and manage images. An image is a lightweight, standalone, and executable software package that includes everything needed to run a piece of software, including the code, runtime, libraries, and settings.

There are three primary ways to create and manage images in Docker:

1. **Manual Creation Using Dockerfile:** Users can write a `Dockerfile` to define the instructions for creating an image. This file includes the base image, required libraries, and commands for setting up the application environment.

2. **Using Pre-built Images from Docker Hub:** Docker Hub is a centralized repository with pre-built images available for download. Users can search for images by description (e.g., `nginx` or `web server`) and deploy them quickly using the `docker run` command.

3. **Creating an Image from a Container:** Once a container is running, its current state can be saved as a new image using the `docker commit` command. This method is useful when modifications have been made inside a container, and these changes must be persisted as an image.

For example, the following command can be used to pull and run an image from Docker Hub:

```
docker run -d --name my_web_server nginx
```

This command downloads the latest `nginx` image and runs it as a container named `my_web_server` in detached mode (`-d`).

4.5.3 Networking and Volumes in Docker

Just like OpenStack, Docker allows the creation of virtual networks to isolate and manage traffic between containers. These networks can be created using different drivers, such as `bridge`, `overlay`, and `macvlan`. Containers can connect multiple networks, allowing flexible communication setups, such as multi-tier applications with separate backend and frontend containers.

In Docker, containers can also be connected to persistent or ephemeral storage. Persistent storage, known as a volume, ensures that data remains intact even if the container is stopped or deleted. Volumes can be created and managed using the following commands:

```
docker volume create my_volume
docker run -d --name my_app -v my_volume:/data my_image
```

In this example, the container `my_app` mounts the volume `my_volume` to its `/data` directory, allowing it to store and retrieve persistent data.

4.5.4 Monitoring and Managing Containers

Once containers are running, monitoring their performance, resource usage, and status is essential. The Portainer dashboard (Figure 4.17) provides a user-friendly interface to start, stop, restart, and delete containers. Additionally, users can view real-time statistics such as CPU usage, memory consumption, and network activity.

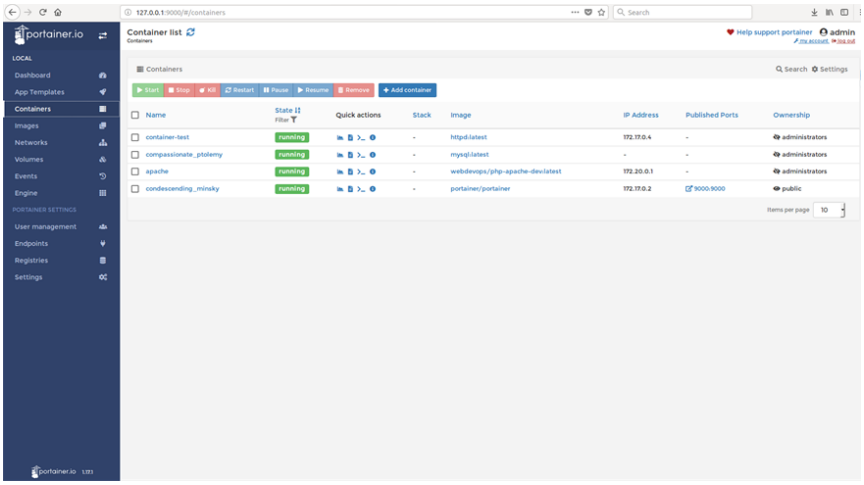

Figure 4.17: Docker Portainer Dashboard: List of running containers and their statistics

For command-line users, Docker provides a rich set of CLI tools for managing containers:

```
docker ps                    # List running containers
docker stop <container>      # Stop a container
docker rm <container>        # Remove a container
docker stats                 # View resource usage statistics
```

4.5.5 Deploying Network Slices Using Containers

In addition to running individual applications, Docker can deploy entire network slices for telecommunication services. Containers offer an advantage over traditional VMs by reducing overhead and improving deployment speed. A network slice can be created by deploying multiple containers representing network elements such as base stations, routers, and gateways.

Once a container is created and configured, a new image can be generated from the running container using a simple command sequence. This process captures the state of the container, including all modifications, and stores it as a reusable image. It is important to note that Docker automatically uploads the newly created image to its image repository, making it readily available for future use. The administrator can easily load and reuse the container image directly from the repository, ensuring consistency across deployments.

Like in OpenStack, Docker allows containers to connect to one or more networks. Additionally, containers can have persistent or ephemeral volumes for storage, which provides flexibility depending on the use case. Persistent storage ensures that data is retained even when the container is stopped or restarted, whereas ephemeral storage is removed once the container ceases to run.

Figure 4.18 illustrates the Docker Containers menu, where administrators can view and manage all active and inactive containers. The interface provides options to stop, start, reinitialize, pause, or delete containers. The menu also includes information about the associated container image, the assigned IP address, and real-time statistics. These statistics help administrators make informed decisions regarding each container's performance and resource usage.

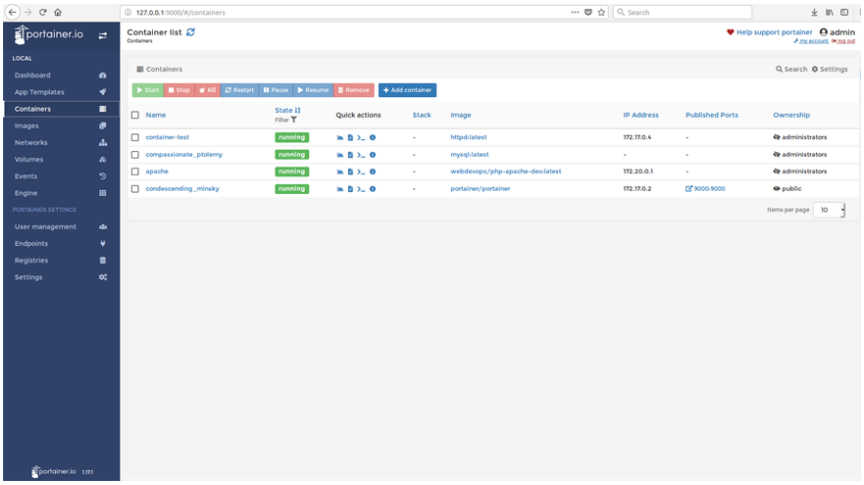

Figure 4.18: Docker Containers menu showing running containers, assigned IP addresses, and available management options

4.5.6 Deploying Network Slices with Docker

Docker containers offer a more agile and efficient alternative to virtual machines when configuring network slices. Unlike virtual machines, Docker containers do not require the initialization of a full operating system, which significantly reduces the overhead associated with launching and running multiple instances. Containers only need to define the necessary functions and libraries, making them lightweight and faster to deploy.

For example, a container can be configured to execute all base station functions, with an assigned IP address. Other containers can be created within the same network to act as routers or gateways. This way, a full network slice can be deployed with multiple interconnected containers, each representing a network function.

However, one of the limitations of Docker in multi-tenant environments is the lack of software isolation between containers, as they all share the same execution cluster and file system. This limitation can challenge scenarios requiring strong isolation between tenants, such as public cloud services. Nevertheless, Docker's efficiency in launching and managing containers makes it an attractive solution for private network slices and scenarios where agility and low overhead are prioritized.

4.6 Conclusions

This section has explored the practical deployment of containers using Docker, highlighting their advantages over traditional VMs regarding resource effi-

ciency, speed, and scalability. Docker's containerization technology allows for the quick and easy deployment of applications, along with persistent and ephemeral storage solutions. Furthermore, Docker's support for virtual networks and integration with tools like Portainer make it an ideal choice for managing large-scale container deployments.

In the context of 5G and network slicing, containers offer the potential for more agile and flexible deployments compared to VMs. However, their lack of kernel-level isolation may pose challenges in multi-tenant environments. Nonetheless, container-based solutions such as Docker are likely to play a critical role in the future of network virtualization, particularly in scenarios where fast deployment, scalability, and efficiency are paramount.

This thesis has proposed a new structure for SC integration in a gateway-controlled network, in which Docker could allow for a flexible, still robust operation of such a network, reducing signaling overheads in the SC. Even without a proper standardization of the proposed solution, this is perfectly compatible with the standard, allow for the fast integration of operators.

Chapter 5

Enhanced Time Synchronization in 5G Private Networks with a TESC

In smart factories, machines and products communicate with each other to enhance the flexibility and automation of the production chain. This vision aligns with the goals of the fourth industrial revolution (*Industry 4.0*), which aims to rely on real-time, wireless, and ultra-reliable communications between raw materials and machines. To address this requirement, Third Generation Partnership Project (3GPP) introduced support for deterministic communications in Fifth Generation (5G) as part of Release 16. Specifically, this release enables the integration of IEEE Time-Sensitive Networking (TSN) over wireless channels, supporting applications that require ultra-reliable low-latency communication (Ultra-Reliable and Low Latency Communications (URLLC)).

This chapter focuses on the integration of TSN with 5G networks based on 3GPP TS 23.501, as outlined in Release 17. It describes time synchronization in the downlink, mapping TSN protocols to 5G System functions. Moreover, the latest enhancements introduced in Release 17, such as uplink synchronization extensions, are presented. The paper also addresses the main security threats discussed in the standard and explores the solutions proposed by 3GPP and IEEE to safeguard the network against potential attacks.

Furthermore, a novel method and architecture are proposed to support TSN over wireless channels in 5G networks by incorporating the TSN synchronization function into small cell Next Generation Node B (gNB). This architecture includes the TSN Translator function in the Small Cell (SC) (Service Level Agreement (SC-TT)), which provides precise time synchronization to mobile

terminals connected to the 5G network. The gNB implements a Generalized Precision Time Protocol (gPTP) (Generalized Precision Time Protocol – IEEE 802.1AS bt) client, enabling a common synchronization domain across multiple small cells within an industrial 5G network.

5.1 Introduction to Industrial IoT and Time-Sensitive Networking

The industry is profoundly transforming as machines are no longer static and wired. Flexibility in reconfiguration has become a key requirement, necessitating the introduction of wireless communications. This shift marks the advent of the Industrial Internet of Things (Industrial IoT (IIoT)) and Industry 4.0 concepts [50]. In Industry 4.0 networks, real-time, ultra-reliable communication is essential for forwarding critical process data. Sensors and actuators, now more intelligent, transmit real-time data alongside other metrics such as energy consumption and maintenance reports. The increasing variety of services and the growing demand for reliability and capacity are pushing wireless architectures to become more interoperable and flexible—leading to the need for 5G networks.

Furthermore, synchronization of industrial processes remains a critical challenge. Some specific examples are outlined in [51]:

- Motion control and control-to-control communication for industrial controllers require less than 1 µs of offset between time clocks.
- Smart grid systems require synchronicity between phasor measurement units (PMUs) with time offsets of less than 1 ms.

These tight restrictions have historically led industrial systems to use specialized protocols to ensure device synchronization. One of the most prominent initiatives in this area is Time-Sensitive Networking (TSN), a set of standards designed to provide time-sensitive transmission over Ethernet networks, enabling interoperability across diverse applications [52].

From its inception, 5G was developed to meet two major industrial challenges: wireless flexibility for Industry 4.0 and low-latency, high-reliability transmission. However, in Release 15, 5G did not yet include provisions for synchronizing entities using a common time source. After this initial release, integrating of TSN into the 5G system became a top priority for standardization efforts, as seamless mobility and reliable connectivity were crucial for realizing Industry 4.0. The consensus is that true Industry 4.0 adoption will only occur after merging these two standards.

Release 16 established a strong foundation for integrating 5G and TSN [53]. In this release, 3GPP defines 5G System (5GS) features that support TSN standards, introducing new entities to translate TSN protocols into internal 5G procedures. This integration can be applied in motion control and

control-to-control scenarios, where a controller sends a downlink timestamp to synchronize actuators for executing specific tasks. Moreover, Release 17 extends TSN integration to uplink synchronization, where machine sensors send timestamps to controllers or monitoring devices, particularly important in use cases such as smart grids [54].

While much of the literature has focused on general aspects of TSN over 5G, simulation-based analyses have explored 5G's ability to achieve clock precision [55] [56]. However, the challenge of integrating a synchronization-capable 5G network into real-world industrial deployments, especially in cases where fully private industrial networks are impractical due to cost, remains unresolved.

This chapter presents the latest advancements in the TSN specification within 3GPP, explaining the principles and operations of synchronization protocols. It includes a detailed explanation of Release 16 features and insights into Release 17 specifications. Although the specification for Release 17 was not finalized at the time of writing, key aspects have been described and summarized. Furthermore, this work discusses how synchronization error can be minimized by implementing the TSN Translator function in Small Cell networks. The implications of this solution from both synchronization and performance perspectives are also explored.

5.2 Basics of Time-Sensitive Networking

A TSN network consists of a Talker end station, which acts as the source, transmitter, or producer of the stream, and one or more Listener end stations, which serve as the destination, receivers, or consumers. These end stations are connected via Bridges, layer two switches that receive and forward TSN messages to the appropriate end stations. The network achieves synchronization using the generalized Precision Time Protocol (gPTP), as specified in IEEE 802.1AS [57]. Additional elements such as the Centralized User Configuration (CUC) and Centralized Network Configuration (CNC) may be added depending on the TSN configuration model. The following sections describe the key components of TSN.

5.2.1 TSN Configuration Models

IEEE 802.1Qcc [58] defines two TSN configuration models with an additional hybrid model. These models differ based on how user and network configuration information flows between the entities in the network (e.g., Bridges, Talkers, and Listeners).

In the centralized model, the CUC is responsible for discovering end stations and retrieving their capabilities and user requirements. The CNC configures Bridges using a management protocol and maintains a global view of the network's physical topology and the capabilities of each Bridge.

In the fully distributed model, end stations exchange user requirements through the connected Bridge, which locally manages its resources. However, each Bridge does not have a global view of the entire network. Although the fully distributed model has advantages, the integration of TSN with 5G System (5GS) has so far focused on the fully centralized model due to its maturity and reliability.

Release 17 of 3GPP is currently studying the option of integrating the fully distributed model of TSN with 5GS. For this to happen, the 5GS would need to interpret and potentially modify TSN stream resource registration messages (e.g., Multiple Stream Reservation Protocol) based on its capabilities. A third hybrid model, combining the benefits of both centralized and distributed architectures, is under study but not yet considered for 5GS integration.

5.2.2 gPTP Messages for Synchronization

In real-time industrial systems, optimal task execution requires logical correctness and precise timing. Synchronization is critical, and gPTP (defined in IEEE 802.1AS) provides high-precision clock synchronization across the network. Time synchronization in gPTP is achieved by sending synchronized time from the Grandmaster (GM) clock to the PTP instances running at each device in the network.

Each instance computes two key intervals: the residence time (the time a sync packet spends in a Bridge) and the path delay (the time the sync packet travels between two PTP instances).

This thesis focuses on two key gPTP messages: Sync and Follow-Up messages, which contain fields essential for synchronization:

- **CorrectionField**: The sum of the path delay and residence time accumulated during the packet's travel, used in Sync or Follow-Up messages.
- **OriginTimestamp**: Indicates the time at the GM when the Sync message was sent. The sum of the CorrectionField and OriginTimestamp gives the synchronized time at the receiving instance.
- **PreciseOriginTimestamp**: Used in Follow-Up messages, indicating the accurate time the GM sent the Sync message.

Sync and Follow-Up messages also include the `twoStep` flag. If this flag is set to TRUE, a Follow-Up message with the `PreciseOriginTimestamp` is sent after the Sync message. If set to FALSE, the Sync message contains the OriginTimestamp and Follow-Up Type Length Value (TLV).

Another key parameter in IEEE 802.1AS is the `RateRatio` (`RR`), which is the ratio between the GM clock frequency and the local clock frequency. Neighboring instances use the `neighborRateRatio` (`nRR`) to adjust their synchronization.

5.3 3GPP 5GS and TSN Architectural Assumptions and Requirements

5.3.1 3GPP 5GS Architecture to Support Time-Sensitive Communication

3GPP Release 16 introduces key features to support time-sensitive communications, as shown in Figure 5.1. The integration is achieved through three entities:

- **TSN Application Function (TSN AF)**: This entity connects to the CNC and translates control and management functions into 5GS-specific signaling.
- **Network Side TSN Translator Network Side TSN Translator (NW-TT)**: Integrated within the User Plane Function (UPF), it serves as the entry point for TSN messages from the Internet into the 5GS.
- **Device Side TSN Translator (DS-TT)**: This translator converts 5G messages for the Listener at the User Equipment (UE) side, assuming the UE is Time Sensitive Communication (TSC)-enabled.

From a TSN perspective, the 5GS acts as a single TSN Bridge, forwarding and updating the `CorrectionField` in gPTP messages traversing it. The NW-TT and DS-TT entities perform this correction. In Release 16, the GM clock is attached to the network for downlink synchronization, while Release 17 introduces uplink synchronization, where the GM synchronizes devices via the 5GS.

5.3.2 Required Protocols for 3GPP 5GS and IEEE TSN Integration

Several TSN protocols must be implemented for effective 3GPP and TSN integration:

- **Link Layer Discovery Protocol (LLDP)**: Defined in IEEE 802.1AB [60], this protocol is used by the NW-TT or DS-TT to advertise their identity, capabilities, and neighbors on the 5GS.
- **Stream Reservation Protocol (SRP)**: Defined in IEEE 802.1Qcc [58], SRP reserves resources for a TSN stream along its entire path. It interacts with the 5GS via the Policy Control Function (PCF).
- **Per Stream Filtering and Policing (PSFP)**: Defined in IEEE 802.1Qci [61], PSFP enhances network robustness by filtering traffic streams and preventing overloads. It is implemented via filters in the UE and UPF.

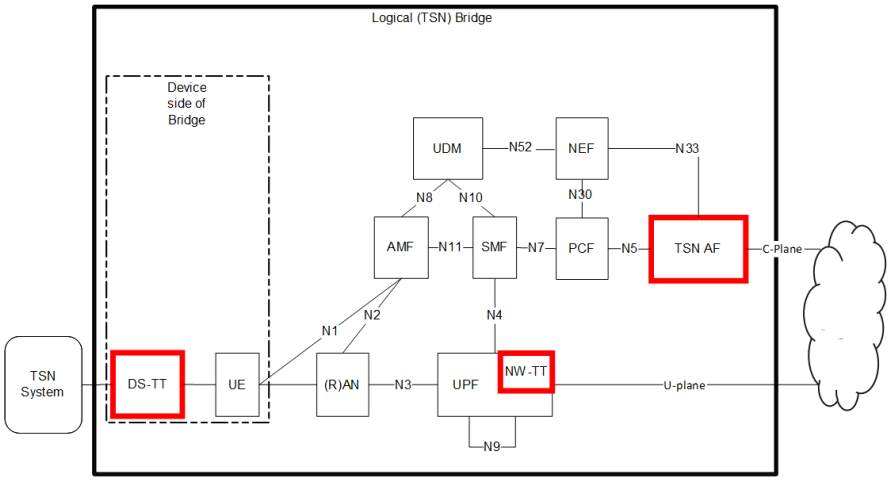

Figure 5.1: System architecture view with 5GS as a TSN bridge [59]

- **Priority Code Point (PCP)**: Defined in IEEE 802.1p [62], PCP allocates priority levels to queues on each TSN port. It is integrated with 5GS by mapping TSN ports to Quality of Service (QoS) flows in Packet Data Unit (PDU) sessions.

The following section will explain how these protocols are applied to integrate TSN with 3GPP 5GS, focusing on the specific synchronization procedures.

5.4 Integration of 3GPP 5GS and IEEE TSN

5.4.1 Procedure of Downlink Synchronization Using a 5G Bridge

Release 16 defines the procedure for downlink synchronization where one or more TSN Grandmasters (GM) are connected to the UPF through the NW-TT. In this configuration, the GM synchronizes the TSN end stations, such as actuators, behind the device. The NW-TT generates an ingress timestamp (Ingress Timestamp (TSi)) upon receiving a Sync or Follow-Up message and stores it in the message's Suffix field. It then computes the cumulative Rate Ratio (RR) and modifies the gPTP message payload by appending the cumulative RR to the Follow-Up TLV of the Follow-Up or Sync message. This updated gPTP message is forwarded to the Device Side TSN Translator (DS-TT) through the UPF.

Upon receiving the message, the DS-TT generates an egress timestamp (Egress Timestamp (TSe)), allowing the DS-TT to calculate the residence time within the 5GS and update the CorrectionField. The final gPTP message is then sent to the end station, which updates its local time to synchronize with the GM. Figure 5.2 illustrates how the synchronization flow is propagated across the gPTP instances, which include the TSN GM, NW-TT, DS-TT, and TSN end stations. In this example, the synchronization from TSN GM to NW-TT uses a two-step transport method, while the synchronization from DS-TT to the end station uses a one-step method. However, the choice of implementation depends on the factory's configuration.

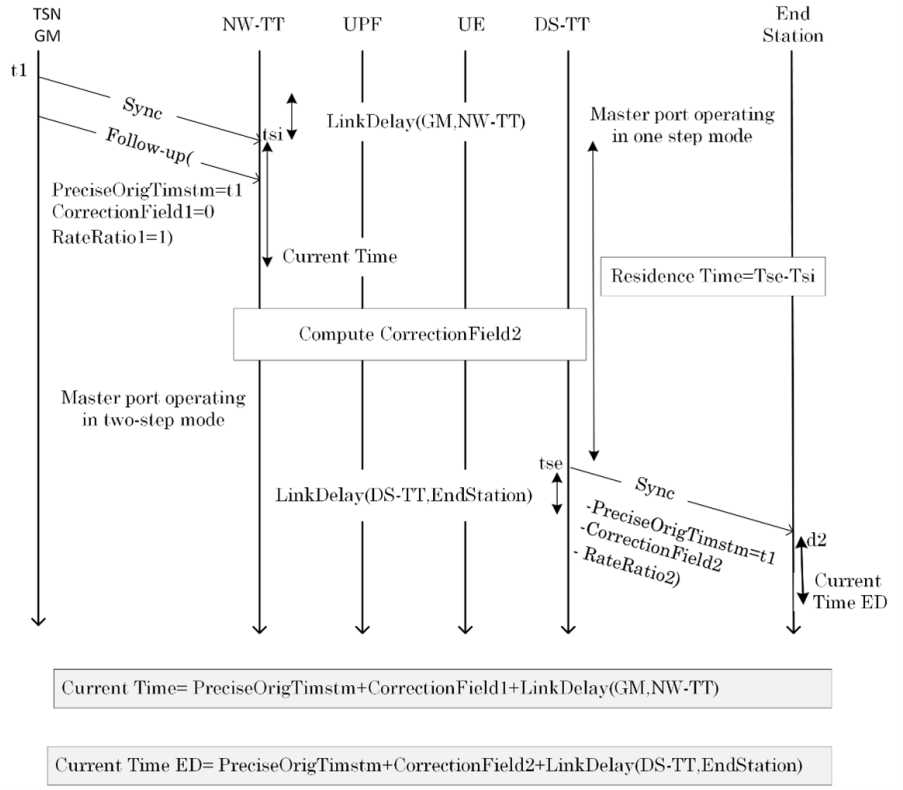

Figure 5.2: Procedure for synchronizing TSN end stations attached to the device (DS-TT) with the TSN GM behind the 5GS (NW-TT)

The TSN GM sends a Sync message to the NW-TT at time t_1, relative to the GM. Since the two-step method is used, the GM later sends a corresponding Follow-Up message, which includes the `PreciseOriginTimestamp`, `CorrectionField1`, and `RateRatio1`. The `PreciseOriginTimestamp1` holds the time at which the GM sent the Sync message (t_1). The `CorrectionField1`

accounts for the difference between the synchronized time when the Sync message was sent and the `PreciseOriginTimestamp1`, which in this case is zero.

$$\texttt{CorrectionField1} = t_1 - t_1 = 0$$

The `RateRatio1` is the ratio of the GM clock frequency to the local clock frequency of the GM, and in this scenario, the values are identical, so:

$$\texttt{RateRatio1} = 1$$

The NW-TT receives the Sync message at time t_{si} on its local clock. After receiving the Follow-Up message, the NW-TT forwards a new Sync message at time t_{se} on its local clock. The NW-TT then computes `CorrectionField2`, which is the difference between the synchronized time corresponding to t_{se} and the `PreciseOriginTimestamp1`. This calculation accounts for the time interval between t_1 and t_{se}, expressed in the GM clock time base. The correction field is then computed as:

$$\begin{aligned}\texttt{CorrectionField2} &= \texttt{Synchronized time}\, t_{\text{se}} - t_1 \\ &= \texttt{LinkDelay(GM,NW-TT)} + \texttt{Residence Time} \times \texttt{RateRatio2}\end{aligned}$$

5.4.2 Procedure for Uplink and UE-UE Synchronization

Uplink (UL) and UE-to-UE synchronization were introduced in 3GPP Release 17. This scenario can be applied to smart grids, where sensors synchronize with each other and with controllers. In this case, the TSN GM is attached to the device side and synchronizes TSN end stations located behind the 5GS, as well as other devices connected to the same UPF.

For UL synchronization, the TSN GM generates Uplink (UL) gPTP messages, and the DS-TT performs the same operations on these UL gPTP messages as the NW-TT does on the Downlink (DL) messages. The steps for UL synchronization are as follows:

1. The TSN GM generates the UL gPTP message.
2. The DS-TT processes the Sync and/or Follow-Up messages received from the TSN GM, similarly to the NW-TT's handling of DL messages.
3. The UL gPTP message is forwarded through the user plane to the UPF, like any data packet. The UPF sends the gPTP message to the Ethernet connection on the N6 interface, enabling other devices on N6 and other DS-TT/UEs connected to a different UPF to receive the gPTP message.
4. Once the NW-TT receives the modified gPTP message, it executes the same steps as the DS-TT when processing DL Sync and/or Follow-Up messages from the UE.

5. Finally, the NW-TT forwards the UL gPTP message to the TSN end station.

5.5 Time Sensitive Communication-enabled Small Cell (TESC)

5.5.1 Concept and Architecture

The advent of indistrial Internet of Things (IoT) and Industry 4.0 requires wireless connectivity, especially in industrial environments where employees and robots move around the factory floor. SCs, in particular, offer significant advantages over macro cells, as they provide easier deployment, higher capacity, and lower latency. SCs are also a viable substitute for millimeter waves in indoor environments, especially where obstacles block signal propagation. In such environments, a movement behind one of these obstacles could cause signal drops. To address this, ultra-dense networks, consisting of a large number of low-power mini base stations, ensure continuous line-of-sight connections. The Small Cell Forum (Small Cell Forum (SCF)) predicts that the deployment of SCs in private and industrial environments will grow by 25% in the next six years [63].

Considering the integration of TSN with 5G, this paper proposes adding TSN synchronization to SCs for industrial automation. In this approach, the function of translating and updating gPTP messages moves to the SC instead of being located on the device side. The synchronization of the device is achieved using a physical-layer procedure that disciplines the device clock, using flank signals extracted from the 5G New Radio (NR) radio frame at each slot or Orthogonal Frequency Division Multiplexing (OFDM) symbol to achieve precise synchronization. The gPTP instance embedded in the SC is referred to as the SC-TT, and its role is to ensure synchronization accuracy in the 5G NR radio frame. As a result, the entire private 5G industrial network is fully synchronized. Transmissions from different cells in a Time Division Duplexing (TDD) network are synchronized to prevent intercell and inter-subframe interference, which is guaranteed by 3GPP standards like Technical Specification (TS) 38.104 [64].

As shown in Figure 5.3, the SC-TT is embedded in the SC and is responsible for translating TSN messages into 5GS signaling. The combination of SC and SC-TT constitutes the TSN-enabled Small Cell (TESC). This new integration provides several benefits to SC manufacturers, as it allows them to expand into factories that incorporate automation into their production processes. Support for TSN synchronization is simplified through the TESC, enabling the use of standard 5G IoT devices by simply upgrading their software to use the TESC network time instead of local or Global Positioning System (GPS) time when the required time accuracy is in the milliseconds range.

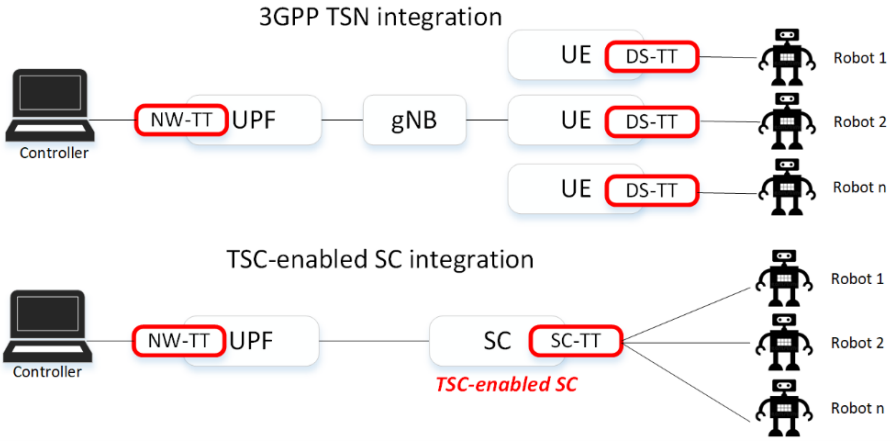

Figure 5.3: Time Sensitive Communication-enabled Small Cell (TESC) versus 3GPP integration

Furthermore, the additional enhancements needed to make 5G IoT devices TSN-capable with high accuracy (1 μs or lower) are minimal. These enhancements do not require significant changes, such as additional processing required to terminate the TSN network in the device. Instead, the 5G radio frame provides time and synchronization through slot indication signals and symbol boundary signals.

5.5.2 End-to-End Synchronization using TESC

The synchronization procedure using TESC consists of two primary phases. The first phase is the end-to-end synchronization between the GM clock and the SC . The second phase involves synchronizing the internal clock of the user equipment (UE) based on timing information provided by the SC using 5G physical layer signals.

Figure 5.4 illustrates the time synchronization mechanism in a 5G-enabled industrial communication system, integrating TSN principles. The architecture ensures precise synchronization between network infrastructure and robotic actuators for deterministic communication. The key components of the figure are:

- **Industry Controller:** Issues commands {`orderType, Time`} and uses a Controller Clock ($\tau_{\text{controller}}$) synchronized with the Grandmaster (GM) Clock via gPTP Generalized Precision Time Protocol.

- **Network Node (UPF) with NW-TT:** Acts as the time distribution center for the 5G system, maintaining a Reference Clock (τ_θ synchronized

with the GM Clock. It ensures precise timing transmission to multiple Small Cells (SC-TTs).

- **Network Devices (SC-TTs** Intermediate time synchronization points with local clocks (τ_1, τ_2, τ_3), ensuring synchronization with the 5G NR radio frame before transmitting time signals to user devices.
- **User Devices (Robots):** Operate based on time signals received from the network, maintaining their own Robot Clocks $(\tau_{\text{robot1}}, \tau_{\text{robot2}})$ for precise real-time operation.

The process of synchronization is as follow:

- The GM Clock distributes time via gPTP.
- The Network Node (UPF + NW-TT) synchronizes all SC-TTs.
- SC-TTs transmit synchronized time to user devices (robots) over the 5G NR radio frame.
- Timing constraints ensure:

$$|\tau_\theta - \tau_1| \leq 1.5\mu s, \quad |\tau_\theta - \tau_2| \leq 1.5\mu s, \quad |\tau_\theta - \tau_3| \leq 1.5\mu s \tag{5.1}$$

$$|\tau_1 - \tau_{\text{robot1}}| \leq 1.5\mu s, \quad |\tau_2 - \tau_{\text{robot2}}| \leq 1.5\mu s \tag{5.2}$$

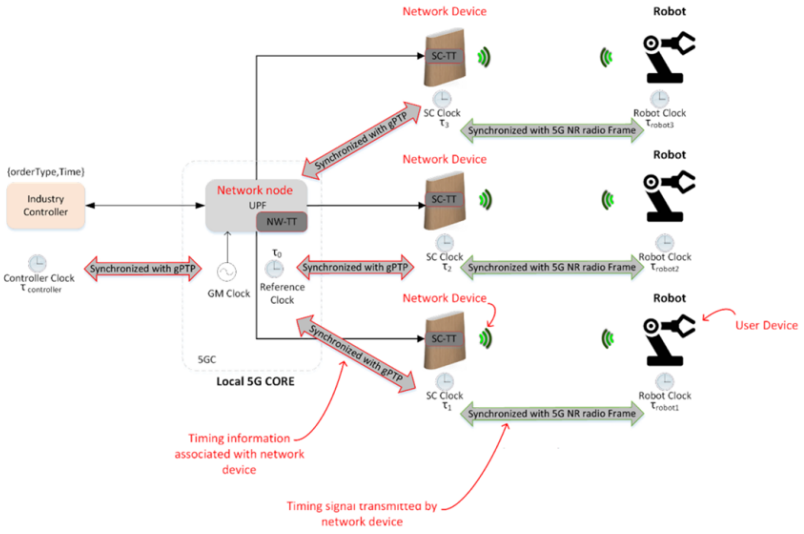

Figure 5.4: Time Sensitive Communication-enabled Small Cell network

The first phase of synchronization, from the GM clock to the SC, is based on IEEE 802.1AS protocols, where the SC acts as the endpoint of the TSN

domain. The second phase involves using the 5G NR radio frame to synchronize the UE with the SC, ensuring precise time coordination between the UE and the rest of the network.

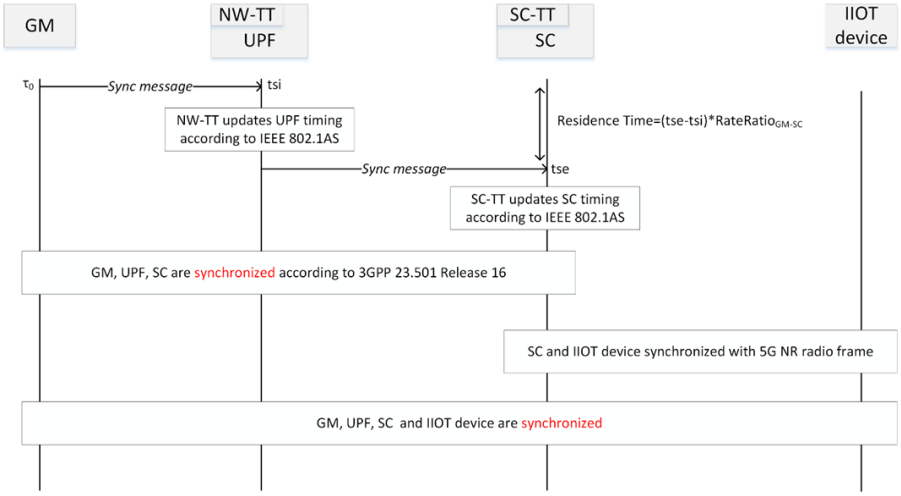

Figure 5.5: End-to-End Synchronization Procedure in 5G Network with TSN

Figure 5.5 illustrates the end-to-end synchronization process within a private 5G industrial network. The architectural components involved include the Grandmaster GM, NW-TT at the UPF, and SC-TT at the SC. The synchronization process ensures accurate timing between the Grandmaster, SC, and industrial IoT devices.

The process begins with the Grandmaster clock (τ_0) sending a Sync message to the NW-TT. Upon receiving the message at time t_{si}, the NW-TT updates the UPF timing according to the IEEE 802.1AS standard. The NW-TT then forwards the Sync message to the SC-TT at time t_{se}. The SC-TT updates the SC's timing based on the received timing information.

The synchronization between the GM,UPF, and SC follows the procedures described in 3GPP TS 23.501 Release 16. The residence time is calculated as:

$$\text{Residence Time} = (t_{se} - t_{si}) \times \text{RateRatio}_{GM-SC}$$

where t_{se} is the time the Sync message arrives at the SC, and t_{si} is the time it arrives at theUPF. The RateRatio is the ratio between the clock frequency of the GM and the SC. Once the SC and the IIoT device are synchronized using the 5G NR radio frame, the indistrial IoT device can achieve synchronization with the GM.

The final step of the process synchronizes the entire system: GM,UPF, SC, and the industrial IoT device ensuring end-to-end synchronization throughout

the 5G network, meeting the precision requirements of TSN-enabled industrial applications.

End-to-End Synchronization from GM to SC

End-to-end synchronization between the GM clock and the SC relies on the exchange of gPTP messages, such as The *Sync* message that carry timing information, such as the packet reference time, link delay, and residence time. The residence time ($T_{\text{residence}}$) represents the time a sync packet spends inside the 5G network, from the point of ingress to the point of egress.

The synchronized time at the SC is computed using the following equation:

$$\tau_{\text{SC}} = \tau_0 + \delta_{\text{link delay}} + T_{\text{residence}}, \tag{5.3}$$

where:

- τ_{SC} is the synchronized time at the SC.
- τ_0 is the reference time from the GM clock.
- $\delta_{\text{link delay}}$ is the propagation time of the sync packet from the GM to the Network Time Translator NW-TT.
- $T_{\text{residence}}$ is the residence time calculated as the difference between the ingress timestamp (t_{si}) and egress timestamp (t_{se}).

The residence time can be expressed as:

$$T_{\text{residence}} = (t_{\text{se}} - t_{\text{si}}) \times \text{RateRatio}_{\text{GM,SC}}, \tag{5.4}$$

where the RateRatio is the ratio of the GM clock frequency to the SC clock frequency. The overall end-to-end synchronization between the GM and the SC is achieved using this method, ensuring that the SC remains in sync with the reference clock in the TSN domain.

Synchronization of the Internal Clock of the UE: Physical Layer-based Synchronization

The second phase of the synchronization process focuses on the internal clock of the UE. The SC transmits timing signals to the UE using physical layer signals from the 5G NR radio frame, such as the slot indication signal and the symbol boundary signal.

The timing advance (TA), which represents the time for the reference signal to travel from the SC to the UE's receiver, is used to adjust the UE's clock. The TA is determined through the Random-Access process. By combining the TA with the slot indication signal, the SC provides precise timing information that allows the UE to synchronize its internal clock with the virtual clock domain of the network.

The synchronized time at the UE is calculated as follows:

$$\tau_{\text{SynchronizedTime}} = \tau_{\text{InternalClock}} - \tau_{\text{TimingAdvance}} \pm \Delta_{\text{SlotIndication}}, \tag{5.5}$$

where:

- $\tau_{\text{SynchronizedTime}}$ is the synchronized time at the UE.
- $\tau_{\text{InternalClock}}$ is the time of the UE's internal clock.
- $\tau_{\text{TimingAdvance}}$ is the timing advance value provided by the SC.
- $\Delta_{\text{SlotIndication}}$ is the difference between the arrival time of the slot indication signal at the UE and the reference time.

The SC ensures that the slot indication signal is transmitted at even intervals relative to the reference clock, allowing the UE to maintain precise synchronization between signals using its internal clock. This synchronization is crucial for ensuring that UEs can coordinate tasks in real-time, especially in applications requiring ultra-reliable low-latency communication (URLLC).

Enhanced Synchronization Accuracy in TSN-Enabled Small Cells (TESC) Compared to PTP

Although the Precision Time Protocol (PTP) (*Precision Time Protocol*, IEEE 1588) is used to synchronize the SC with the GM clock, TESC achieves **better synchronization accuracy** for UEs through additional refinement mechanisms. The key difference lies in how synchronization is propagated and refined at different layers of the network.

PTP Synchronization for Small Cells: PTP is responsible for synchronizing the SC clock with the GM clock using gPTP (*Generalized Precision Time Protocol*, IEEE 802.1AS). This achieves an accuracy of **sub-microsecond (1 s)**, but its effectiveness is limited by:

- **Network jitter and delay variations** due to residence time and propagation delay.
- **Periodic synchronization updates** instead of continuous real-time corrections.
- **Lack of direct wireless transmission compensation**, as PTP primarily operates in the wired domain.

However, PTP alone does not directly synchronize the UE; it ensures that the SC is in sync with the TSN reference clock.

TSN-Enabled Small Cell Synchronization for UEs TESC extends synchronization beyond PTP by leveraging the **5G NR physical layer**, introducing several refinements that improve the final synchronization accuracy at the UE:

1. **5G NR Radio Frame Alignment**: Once the SC is synchronized with the GM clock via PTP, it transmits timing signals directly to the UE using:
   - **Slot Indication Signal** – Ensures frame-level alignment.
   - **Symbol Boundary Signal** – Enables fine-grained time alignment.
   - **Timing Advance (TA)** – Compensates for wireless propagation delay.
2. **Wireless Propagation Delay Compensation**: Unlike PTP, which operates in the wired domain, TESC accounts for additional transmission delays due to wireless propagation.
3. **Continuous Synchronization Updates**: While PTP operates with periodic sync updates, 5G NR ensures **real-time synchronization adjustments** through slot-based and sub-slot timing corrections.
4. **Higher Granularity**: The synchronization achieved using 5G NR mechanisms can reach 100 ns-level precision, compared to the typical sub-microsecond ($\leq 1\ \mu$s) precision of PTP alone.

Mathematical Representation The synchronization at the UE is refined using:

$$\tau_{\text{SyncUE}} = \tau_{\text{GM}} + \delta_{\text{link delay}} + T_{\text{residence}} - \tau_{\text{TimingAdvance}} \pm \Delta_{\text{SlotIndication}}, \quad (5.6)$$

where:

- τ_{SyncUE} is the final synchronized time at the UE.
- τ_{GM} is the reference time from the Grandmaster clock.
- $\delta_{\text{link delay}}$ is the wired propagation delay.
- $T_{\text{residence}}$ is the residence time of the Sync packet in the 5G network.
- $\tau_{\text{TimingAdvance}}$ compensates for wireless propagation delay.
- $\Delta_{\text{SlotIndication}}$ refines the final timing offset.

In Summary, while PTP provides the baseline synchronization for the SC, TESC refines and extends this synchronization to the UE using:

- 5G NR frame-based alignment mechanisms.

- Wireless propagation delay compensation.
- Real-time slot-based synchronization updates.

These additional enhancements result in **better synchronization accuracy at the UE level** compared to PTP alone, making TESC a more effective solution for URLLC and time-sensitive industrial applications.

5.6 Conclusions

The integration of TSN with 5GS presents significant advancements in achieving the goals of Industry 4.0 and industrial IoT. The combination of ultra-reliable, low-latency communications provided by 5G and the deterministic time-sensitive networking capabilities of TSN creates a robust framework for industrial automation.

As outlined in Section 5.1, the evolution of industrial systems from wired and static configurations to highly dynamic, wireless-enabled environments has brought about a pressing need for synchronization and flexibility. The increasing reliance on wireless communications in manufacturing processes, such as motion control and smart grids, further emphasizes the importance of ensuring tight synchronization between devices and controllers. The introduction of TSN into industrial networks has provided a solution for achieving high-precision synchronization, and the integration of TSN into 5GS (as discussed in Section 5.2) aims to bring these capabilities to wireless environments.

The integration of TSN into 5GS is built upon a well-established foundation, starting with Release 16, which introduced key architectural elements such as the TSN Application Function (TSN AF), the Network Side TSN Translator (NW-TT), and the Device Side TSN Translator (DS-TT), as described in Section 5.3.1. These entities enable the 5GS to act as a transparent bridge, facilitating the transport of critical time-sensitive data between devices and controllers. The Release 17 extension to uplink synchronization, as discussed in Section 5.4.2, further enhances the system's ability to synchronize data from machine sensors to controllers in use cases such as smart grids.

In Section 5.3.2, the protocols necessary for the seamless integration of TSN and 5GS were outlined, including LLDP, SRP, PSFP, and PCP. These protocols ensure that the 5GS can handle the stream reservation, filtering, and priority management needed to maintain network robustness and prevent overloads in an industrial setting. The detailed synchronization procedures presented in Section 5.4.1 and Section 5.4.2 demonstrated how the system handles downlink and uplink synchronization, ensuring that all devices within the network remain synchronized with the Grandmaster (GM) clock.

A key contribution of this work is the introduction of Time-Sensitive Communication-enabled Small Cells (TESC), as described in Section 5.5. TESCs provide a practical and scalable solution for industrial deployments by incorporating TSN functionality directly into small cells, thus extending the

applicability of TSN synchronization to private 5G industrial networks. This enables industries to leverage standard 5G IoT devices with minimal modifications, as discussed in Section 5.5.1. The end-to-end synchronization procedure using TESC, described in Section 5.5.2, ensures that all devices within a network are synchronized to a common time source, achieving synchronization accuracy as low as 54 ns in typical industrial environments.

Drawing from the analysis of the current state of the art 2.3.2, the precision of Over-The-Air synchronization (OAS) is contingent upon the type of device. For UE equipped with PTP support, the precision level is achieved at less than 1 µs. Conversely, low-cost and low-energy UEs lacking PTP support can ensure an accuracy level of less than 10 µs [10–13]. Employing TESC ensures an accuracy level within the range of 0.01 µs to 1 µs, even for economical and energy-efficient UEs lacking PTP support. 5.1 provides a summary of this comparison, note that methods a), b), and c) are explained in 2.3.2.

Type of UE	**UE with no PTP**	**UE with PTP**	**All type of UE**
Sync method	(c)	(a) and (b)	TESC
Accuracy	< 10 µs	< 1 µs	0.01 µs–1 µs

Table 5.1: Synchronization methods and accuracy levels for different types of UEs

In conclusion, the integration of TSN with 5GS represents a significant step forward in realizing the full potential of Industry 4.0. The solutions proposed in this work, particularly the use of TESCs, offer a practical path toward achieving high-precision synchronization across wireless networks. Future work should focus on the practical implementation of these solutions in real-world industrial environments to validate their performance and identify areas for further optimization.

Chapter 6

5G Physical Layer-Based Procedure to Support Time Sensitive Networking

6.1 Introduction

In modern wireless communication systems, precise synchronization between the User Equipment (UE) and the network is essential, particularly for applications that require Time-Sensitive Networking (TSN), such as those in industrial environments. The advent of Fifth Generation (5G) networks has paved the way for achieving highly accurate synchronization, which is critical for ensuring the timely transmission and reception of data, thus maintaining the reliability of time-sensitive applications.

In this chapter, we explore an innovative synchronization mechanism that leverages the physical layer of the 5G network to achieve precise time synchronization between the UE and the Small Cell (SC). This mechanism is based on timing information derived from the synchronization signals transmitted by a Grandmaster (GM) to the SC, which then relays the timing information to the UE. Using a combination of Timing Advance (TA), residence time, and reference signal timing, the SC calculates the necessary timing adjustments to synchronize the UE's internal clock with the network's virtual clock domain.

The core of this synchronization process lies in transmitting a physical layer signal, specifically the slot indication signal or symbol boundary signal, sent by the SC to the UE. This signal, timed to reach the UE at even intervals, enables the UE to maintain synchronization with the reference clock. By employing a feedback circuit, the UE continuously adjusts its internal clock flank to align with the timing signals received from the SC, thereby maintaining precise synchronization over time.

This chapter also addresses the challenges in this synchronization process, such as the estimation of path delay and time-of-arrival errors. We present a novel approach that optimizes the use of the slot indication signal to minimize these errors, ensuring that synchronization requirements of 1 µs or better can be achieved in integrated 5G and TSN systems. Furthermore, as supported by our research findings, we highlight the importance of optimizing synchronization frequency and improving reference time granularity to reduce synchronization errors.

The synchronization method detailed in this chapter represents a significant advancement in achieving Ultra-Reliable and Low Latency Communications (URLLC) in 5G-enabled industrial applications. This method provides a strong foundation for further innovations in wireless time-sensitive networking. Moreover,this chapter discusses the physical layer-based synchronization between SC and UE, leveraging 5G physical layer signals for enhanced accuracy in Time Sensitive Communication (TSC).

6.2 Literature Review

The evolution of the 5G physical layer has been central to the advancements in wireless communication technologies, providing the foundation for high data rates, low latency, and enhanced reliability. This review discusses the key developments in the 5G physical layer, highlighting the reasons behind its adoption and integration in modern communication systems.

The physical layer of the 5G network is designed to meet the stringent requirements of various emerging applications, including Enhanced Mobile Broadband (eMBB), URLLC, and massive Machine Type Communications (mMTC). One of the main drivers for its evolution has been the need for higher spectral efficiency and support for a wide variety of frequency bands, including millimeter-wave (mmWave) frequencies. According to [65], 5G introduces new waveform designs and multiple access schemes, such as Orthogonal Frequency Division Multiplexing (OFDM) with scalable numerologies, enabling adaptability to different deployment scenarios and applications.

Introducing massive Multiple-Input Multiple-Output (MIMO) technology is another cornerstone of the 5G physical layer. It allows for using many antennas at the base station to increase spectral efficiency and capacity through spatial multiplexing. As outlined in [66], massive MIMO enables beamforming and beam management, which are crucial for handling the challenges of mmWave communication, such as increased path loss and susceptibility to blockages.

The 5G physical layer incorporates several key features that distinguish it from its predecessors, such as 4G LTE. One of the most notable innovations is the flexible numerology system, which allows for variable subcarrier spacing and symbol duration based on the use case and deployment scenario. This

flexibility provides better support for high-speed and low-latency applications, as discussed in [67].

Moreover, 5G supports a wider range of frequency bands, including sub-6 GHz and mmWave frequencies. The ability to utilize mmWave frequencies is particularly significant, as it allows for data transmission at extremely high speeds, albeit with limited range and increased sensitivity to obstacles. The authors in [68] emphasize that mmWave communication can dramatically increase data throughput, making it ideal for applications such as Virtual Reality (VR) and high-definition video streaming.

The 5G physical layer has been designed to support a wide variety of use cases and to meet the increasingly demanding requirements of modern wireless communication. Its flexibility and adaptability are the primary reasons for its widespread adoption. As discussed by [69], the 5G physical layer enables a diverse range of applications, from autonomous vehicles and smart cities to industrial automation and the Internet of Things (IoT). These applications require extremely low latency and high reliability, both of which are facilitated by the features of the 5G physical layer.

The need for URLLC in mission-critical applications, such as remote surgery and autonomous driving, has driven the adoption of the 5G physical layer's features, particularly its ability to provide millisecond-level latency and packet delivery reliability. The authors in [70] argue that these capabilities are fundamental to ensuring the safety and efficiency of next-generation industrial systems.

Furthermore, the scalability of the 5G physical layer allows for the support of massive Machine Type Communication (MTC), which is essential for connecting billions of IoT devices. This scalability is achieved through advanced multiple access techniques, such as non-orthogonal multiple access (NOMA), which enables multiple users to share the same frequency resources efficiently [71].

Despite the remarkable advancements introduced in the 5G physical layer, several challenges remain, particularly regarding supporting URLLC and the stringent accuracy requirements in massive MTC. URLLC, a core enabler for critical applications such as autonomous vehicles, industrial automation, and remote surgery, demands sub-millisecond latency and near-perfect reliability. However, consistently achieving such stringent performance metrics across diverse deployment scenarios remains a significant challenge.

Using mmWave frequencies in 5G while enabling high data rates introduces limitations due to their susceptibility to signal blockages and environmental factors. As highlighted by [72], mmWave communication is highly sensitive to path loss and signal degradation, necessitating the development of more advanced beamforming techniques and efficient antenna designs to maintain reliable connections in real-world environments. In highly dynamic scenarios such as smart factories, this poses a significant challenge for maintaining the high reliability demanded by URLLC.

Moreover, the 5G physical layer's current design, while providing flexibility through scalable numerologies and advanced error correction techniques, still struggles to fully meet the extremely low-latency and high-reliability requirements under high device density, as encountered in massive MTC scenarios. As pointed out in [70], the massive connectivity required by massive MTC—where billions of devices must reliably communicate in real-time—places enormous stress on the physical layer's resources. The non-orthogonal multiple access (NOMA) technique, proposed to increase the capacity and spectral efficiency of mMTC, still requires significant refinement to handle the high traffic loads while maintaining low latency and reliable data delivery, as discussed in [71].

Another pressing challenge lies in achieving the high precision synchronization necessary for URLLC and massive MTC, particularly in time-sensitive applications. The current implementations of synchronization mechanisms, such as those based on the generalized Precision Time Protocol (gPTP), are not yet fully optimized for the microsecond-level accuracy required in critical communication systems. As indicated by [66], while massive MIMO and beamforming provide solutions for spatial multiplexing, they also introduce complexities in timing and synchronization due to the increased number of antennas and the mobility of users. These complexities highlight the need for enhanced synchronization methods to meet the sub-microsecond timing precision demanded by next-generation industrial applications.

In summary, while the 5G physical layer has made significant strides, further enhancements are still needed to fully support the rigorous requirements of URLLC and massive MTC. Continued research and development are essential to optimize mmWave reliability, reduce latency in highly dense environments, and improve synchronization accuracy to meet the demands of mission-critical applications and the IoT.

In 5, we explored the end-to-end synchronization process, starting from the GM, passing through the SC, and ultimately reaching the internal clock of the UE. In the next section, we will focus on the final stage of this process.

6.3 Using 5G Physical Layer Signal for TSN Synchronization

This thesis proposes using the slot indication signal from the 5G New Radio (NR) frame for TSN synchronization. This method allows the UE to synchronize with the SC clock independently of its internal clock capabilities [54]. We achieve precise synchronization with minimal error by leveraging physical layer signals such as the slot indicator. Figure 6.1 demonstrates the timing alignment using the slot indicator.

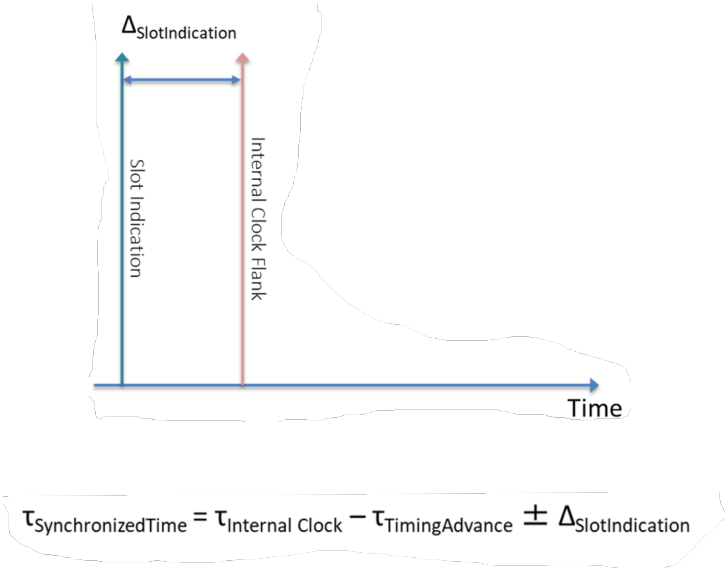

Figure 6.1: Slot indicator signal for 5G and TSN synchronization

6.3.1 Time-Locked Loop (TLL) for Enhanced Synchronization

The Time-Locked Loop (TLL) system is an advanced phase alignment and synchronization circuit. Unlike the traditional Phase-Locked Loop (PLL), the TLL operates in the time domain, which is ideal for high-precision synchronization [73]. Figure 6.2 shows the TLL feedback circuit that adjusts the UE's clock.

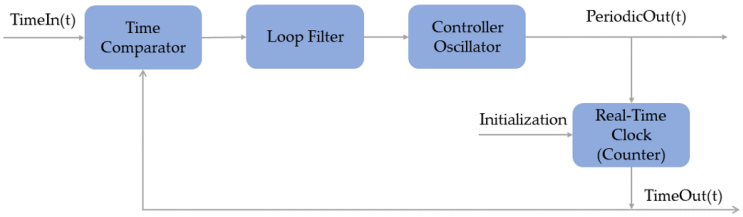

Figure 6.2: TLL feedback circuit for enhanced synchronization

The TLL contains the following components:

- **Controlled Oscillator**: Generates periodic timing signals.
- **Real-Time Clock**: Counts time based on signals from the oscillator.

- **Time Comparator**: Compares computed time with reference signals.
- **Loop Filter**: Filters comparison results and adjusts the oscillator.

6.3.2 Slot Indication in 30 kHz Subcarrier Bandwidth

For synchronization, the SC transmits slot indication signals at even intervals, synchronized with the reference time. With a subcarrier spacing of 30 kHz, the slot duration is 500 µs, allowing the SC to transmit a slot indication signal every 500 µs, as shown in Figure 6.3. Table 6.1 shows the regularity of slot indicator signals.

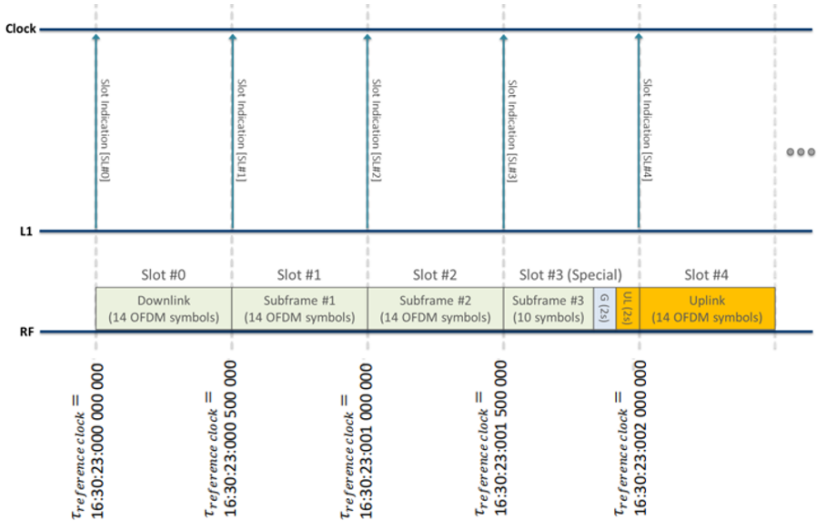

Figure 6.3: Subcarrier bandwidth and slot indicator signal regularity

Subcarrier BW (kHz)	Number of Slots	Slot Indicator Regularity (µs)
15	1	1000
30	2	500
60	4	250
120	8	125
240	16	62.5

Table 6.1: Slot indicator signal regularity with different subcarrier bandwidths

6.4 OFDM Symbol-based Synchronization and Implementation of Time Sensitive-Enabled Small Cell

OFDM symbol-based synchronization provides more frequent and precise reference points for time adjustments within each slot. Each OFDM symbol is a synchronization point, offering finer granularity for timing corrections than traditional slot-based synchronization mechanisms. The frequent reference points allow for real-time adjustments, significantly improving synchronization accuracy, particularly in environments where multipath propagation may introduce timing errors.

Multipath propagation is a phenomenon where signals take different paths to the receiver due to reflections, diffractions, or scattering from various objects in the environment. This often results in signal arrival delays and phase shifts, which can degrade synchronization performance. By leveraging multiple reference points within each slot, OFDM symbol-based synchronization helps mitigate these errors, providing a robust synchronization solution for time-sensitive industrial applications.

The OFDM symbols are transmitted across multiple orthogonal subcarriers within each slot. Since each symbol has a distinct start and end point, the system can perform synchronization adjustments at the onset of each symbol, resulting in more accurate time alignment. This frequent correction mechanism is particularly valuable for time-sensitive networks (TSN) where achieving precise synchronization is critical for mission-critical applications.

Utilizing OFDM symbol boundaries for synchronization minimizes the discrepancy between the disciplining signal (symbol boundary) and the reference clock. This approach addresses the stringent requirements of time-sensitive networking applications, such as industrial automation, collaborative robotics, and real-time control, where synchronization accuracy must be maintained within microsecond-level precision.

To demonstrate the application of OFDM symbol-based synchronization, we discuss an exemplary implementation of a TSN system integrated with a 5G SC network. In a TSN-enabled 5G SC network, both the SC and UE are synchronized to a common network time. The synchronization process involves the transmission of radio frames with a timing advance that ensures the physical layer signals are aligned with the time encoded in the frame. This method ensures the UE's internal clock remains synchronized with the network time throughout the communication process.

The network architecture consists of a 5G SC that transmits timing information to the UE via the physical layer signals of the radio frame. The interface between the modem and the main processor in the UE includes a clock signal that is synchronized with the network time. The modem extracts synchronization signals from the 5G NR frame, such as the Primary Synchronization Signal (PSS) and the Secondary Synchronization Signal (SSS). These

signals maintain synchronization between the UE's local clock and the network time. Integrating 5G SC with TSN guarantees synchronization accuracy of less than 1 µs, making it suitable for URLLC requirements.

This architecture is highly beneficial for applications requiring ultra-precise synchronization, such as collaborative robotics, high-precision manufacturing, real-time control systems, and industrial automation. These applications demand synchronization accuracy of less than 1 µs to ensure real-time coordination and control of multiple devices or systems. For instance, in collaborative robotics, multiple robots must work together coordinated, executing tasks with minimal latency and maximum precision. Similarly, machines must perfectly synchronize in high-precision manufacturing environments to ensure product quality and production efficiency.

The combination of OFDM symbol-based synchronization and the TSN-enabled 5G SC network allows the system to meet the stringent timing requirements of such applications. The frequent synchronization reference points provided by the OFDM symbols ensure that timing adjustments can be made regularly, minimizing synchronization errors and enhancing overall system performance.

The Time Sensitive-Enabled 5G SC network, leveraging OFDM symbol-based synchronization, is well-suited for industrial applications requiring ultra-accurate synchronization and low-latency communication. The following are some key applications that benefit from this network:

- **Collaborative Robotics:** In environments where multiple robots work together, synchronization is critical to ensure coordinated task execution. The precise synchronization enabled by the 5G SC network ensures that robots can communicate and operate in real time, preventing collisions and improving efficiency.

- **High-Precision Manufacturing:** Manufacturing processes often require machines to work together with millisecond-level precision to ensure product quality. The synchronized network allows machines to operate harmoniously, reducing errors and improving throughput.

- **Real-Time Control Systems:** Control systems, such as those used in smart grids or autonomous vehicles, require real-time feedback and control actions. The 5G SC network ensures that control signals are transmitted and received with minimal latency, allowing for timely adjustments and ensuring system stability.

- **Industrial Automation:** In industrial automation, various sensors, controllers, and actuators must be synchronized to maintain efficient operations. The 5G SC network ensures that all system components operate in sync, enabling precise control and monitoring of industrial processes.

In summary, integrating OFDM symbol-based synchronization within the 5G SC network offers a powerful solution for achieving ultra-accurate synchronization in time-sensitive applications. By providing more frequent reference points for synchronization adjustments and leveraging the flexibility of 5G NR, this system meets the stringent timing requirements of industrial automation, collaborative robotics, and other mission-critical applications.

6.4.1 Performance Evaluation

Numerical evaluations were conducted to assess the performance of Over-the-Air time Synchronization (OAS) using the method proposed. For these results, we have used 3GPP-defined values of UE timing errors, given by [74], ensuring that the UE can afford up to ±0.1 ppm relative error, which is 0.2 µs clock drift per second assuming errors in both sides of the communication. Under this assumption, the network would only need to deliver the GM reference time at most every five seconds to remain within the 1 µs accuracy requirement. Moreover, the reference time granularity is 10 ns [75], which means that, once the UE gets a message containing the reference time from the GM, it gets its maximum accuracy that would start degrading at a pace of 0.2 ns per millisecond. In the analysis, the UE could synchronize every slot, via the Slot Indicator Signal, or could synchronize after several slots.

Figure 6.4 plots the UE's synchronization accuracy depending on the Slot Indicator Signal period or, in other words, depending on how often the UE performs the synchronization process using the TSN-enabled Small Cell (TESC). If the synchronization is made every slot, the accuracy would remain at 10 ns, but if the period of synchronization increases, after 50 ms, the drift would start affecting the accuracy. In the limit, if no resynchronization is made in any slot, the clock drift would reach 1 µs in 5 s, in which a new reference time would be provided to the UE in the application layer. Next, we analyzed the impact of the number of UEs that need synchronization with the GM on the consumption of Resource Blocks (RBs). In this evaluation, we considered a 5G numerology with a Subcarrier Spacing (SCS) of 15 kHz and a bandwidth configuration of 10 MHz, resulting in a maximum of 52 RBs per slot, equivalent to 260,000 RBs over a 5-second period [76]. Assuming that the GM reference time can be encoded within 76 bytes [77], this corresponds to approximately 4 RBs using Quadrature Phase Shift Keying (QPSK) modulation with a $\frac{1}{2}$ code rate. Figure 6.5 presents the RB consumption rate as a function of the number of users in a cell. With the proposed TESC method described in this work, only 0.0015% of the available RBs are dedicated to broadcasting the GM reference time.

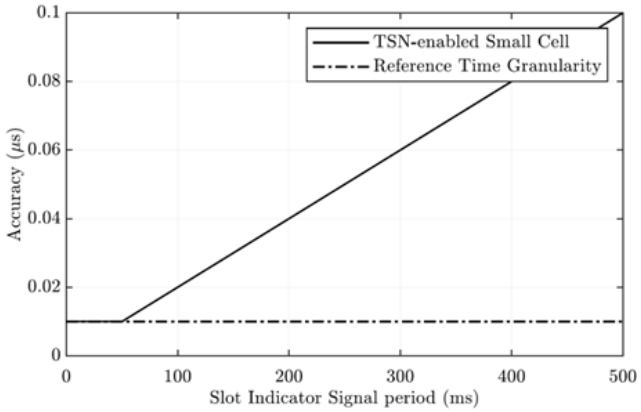

Figure 6.4: UE synchronization accuracy vs. Slot Indicator Signal period for TSN-enabled Small Cell

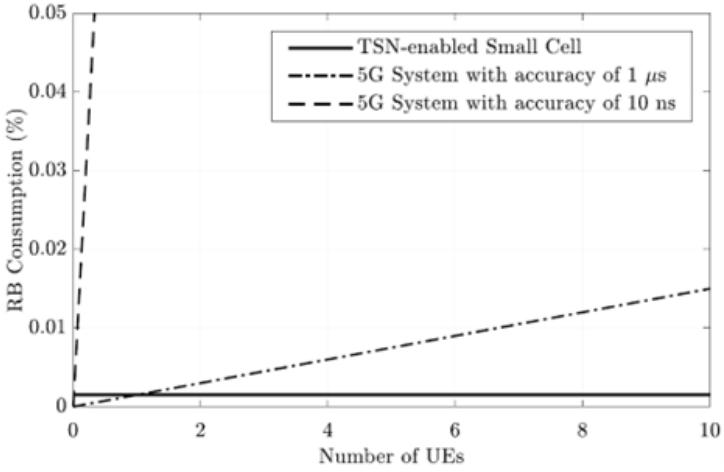

Figure 6.5: Resource Block consumption rate as a function of the number of UEs in the cell, comparing the proposed TESC approach with conventional 5G synchronization methods

This time reference is transmitted once every 5 seconds to all UEs in the cell, and the RB consumption rate remains constant irrespective of the number of UEs. This characteristic makes the TESC approach particularly advantageous in high-density scenarios where a large number of UEs require synchronization with an accuracy level below 1 µs. In contrast, a conventional 5G synchronization scheme with a similar accuracy of 1 µs exhibits increased RB consumption as the number of UEs requiring synchronization grows. This de-

mand on resources is further amplified in scenarios demanding a more stringent 10 ns synchronization accuracy. In such cases, the GM reference time must be broadcasted every 50 ms to each UE individually to maintain the required 10 ns synchronization accuracy. This frequent transmission significantly increases the consumption of RB, as each synchronization message requires dedicated resources within the 5G NR frame. Unlike the 1 μs synchronization scenario, where the GM reference time is transmitted once every 5 seconds and shared among all UEs, the 10 ns accuracy requirement necessitates repeated transmissions at much shorter intervals.

Furthermore, as the number of UEs increases, the total RB consumption scales proportionally, given that each UE requires an individually received synchronization message to compensate for unique propagation delays and clock drifts. In ultra-dense networks, this per-UE synchronization overhead can lead to a substantial allocation of radio resources, limiting bandwidth availability for other services. Without an efficient synchronization mechanism such as the TESC approach, the scalability of high-precision timing in 5G networks would be significantly constrained by excessive RB utilization.

This comparison underscores the efficiency of the TESC method in minimizing resource utilization for synchronization purposes, making it well-suited for applications in ultra-dense networks and mission-critical IoT scenarios where maintaining high synchronization accuracy for numerous devices is essential. The scalable nature of TESC ensures that resource usage remains minimal, even as network demand and user density increase.

In summary, the TESC solution offers a significant reduction in resource consumption compared to traditional 5G synchronization techniques, particularly in large-scale deployments requiring high synchronization precision. The effectiveness of this method becomes increasingly apparent in dense network environments where the demand for ultra-precise timing across numerous devices continues to grow. This approach not only conserves resources but also ensures sustained synchronization accuracy, addressing a critical requirement in next-generation networks and URLLC applications.

6.5 Conclusions

This chapter has explored the use of 5G physical layer signals for achieving precise synchronization in integrated 5G and TSN networks. The novel approach of using slot indication signals, combined with the Time-Locked Loop (TLL) feedback system, demonstrates the feasibility of meeting synchronization requirements for Industrial IoT applications. The findings support achieving synchronization accuracy down to 1 µs or better, enabling the development of highly synchronized and reliable industrial networks.

The integration of OFDM symbol-based synchronization within the 5G SC network offers a powerful solution for achieving ultra-accurate synchronization in time-sensitive applications. By providing more frequent reference points

for synchronization adjustments and leveraging the flexibility of 5G NR, this system meets the stringent timing requirements of industrial automation, collaborative robotics, and other mission-critical applications.

The use of OFDM symbol-based synchronization and the TLL feedback system ensures accurate time alignment and real-time adjustments, particularly in environments with multipath propagation and where ultra-low latency communication is essential. The synchronized 5G SC network is ideally suited for applications such as collaborative robotics, high-precision manufacturing, real-time control systems, and industrial automation, all of which require synchronization accuracy of less than 1 µs.

The chapter advances URLLC capabilities in industrial settings by utilizing these innovations, providing a robust platform for TSN-enabled, ultra-reliable, low-latency communications across various industries.

Chapter 7

Conclusions and Future Work

7.1 Conclusions

This thesis has presented a comprehensive analysis of the integration of Small Cells (SC) into Fifth Generation (5G) networks, with a particular focus on enhancing Time-Sensitive Networking (TSN) capabilities through 5G physical layer-based synchronization mechanisms. The research explored various aspects of achieving ultra-precise synchronization, which is a critical requirement for Ultra-Reliable and Low Latency Communications (URLLC) applications in industrial environments. The proposed methodologies have been demonstrated to meet the stringent requirements of time-sensitive applications, where synchronization accuracy plays a crucial role in ensuring the reliability and performance of communication networks.

One of the most significant contributions of this work is the introduction of the Time-Sensitive Communication-enabled Small Cell (TESC) architecture. By integrating Small Cell (SC) into the 5G network, we achieved a new level of synchronization precision, which is essential for enabling industrial applications such as collaborative robotics, real-time control systems, and high-precision manufacturing. The TESC architecture leverages the physical layer of the 5G network to ensure that synchronization signals are transmitted with the accuracy required by these critical applications.

In Chapter 5, we detailed the end-to-end synchronization process from the Grandmaster (GM) to the User Equipment (UE), passing through the SC. This approach utilizes advanced timing information such as Timing Advance (TA), residence time, and reference signal timing, enabling synchronization between the SC and the UE. Through the use of slot indication signals and symbol boundary signals, we demonstrated how synchronization between the SC and UE can be maintained with a high degree of precision. These find-

ings underscore the potential for 5G to meet the demands of future industrial applications, where timing accuracy is measured in microseconds or better.

Moreover, we introduced the Time-Locked Loop (TLL) feedback system as a novel synchronization circuit for precise time alignment. The TLL operates in the time domain, making it more suited to applications where timing precision is critical. Unlike traditional Phase-Locked Loops (PLL), the TLL provides a higher level of synchronization precision, ensuring that even small timing errors are corrected in real-time.

The challenges of mitigating timing errors caused by multipath propagation were addressed by employing a novel method that optimizes the use of the slot indication signal. By enhancing the granularity of reference time and reducing the error associated with time-of-arrival estimation, we successfully minimized synchronization errors, achieving the synchronization accuracy of 1 μs or better. This level of precision is critical for URLLC and TSN systems, which require reliable and deterministic communication.

The contributions of this thesis can be summarized as follows:

- **TESC Architecture**: A novel architecture for integrating SC with 5G to support TSN and achieve microsecond-level synchronization accuracy in industrial environments.
- **Physical Layer-based Synchronization**: Utilization of physical layer signals such as slot indication and symbol boundary signals to maintain time synchronization between the SC and UE.
- **Time-Locked Loop (TLL)**: A time-domain synchronization circuit designed to provide high precision in time alignment for industrial applications.

This work sets a solid foundation for future advancements in time-sensitive networking within 5G-enabled industrial applications. The techniques and methodologies presented in this thesis contribute to the state of the art by providing a practical solution for achieving ultra-precise synchronization in environments where timing accuracy is paramount.

7.2 Future Work

Despite the significant contributions of this thesis, there are several avenues for future research and development that could further enhance the capabilities of 5G networks in supporting TSN and URLLC applications. As the demands on industrial communication systems continue to evolve, the following areas present opportunities for future exploration:

7.2.1 Real-World Implementation and Field Testing

While the proposed TESC architecture and synchronization mechanisms have been validated through simulations and theoretical analysis, the next logi-

cal step involves deploying these solutions in real-world industrial environments. Testing the TESC architecture in a live 5G network, with actual industrial equipment such as collaborative robots, high-precision manufacturing machines, and autonomous systems, will provide valuable insights into its practical applicability. Field testing will help assess the performance of the synchronization mechanisms under real-world conditions, including interference, mobility, and varying network loads.

Moreover, practical deployment will allow for the evaluation of the scalability of the TESC architecture in large industrial setups where hundreds or even thousands of devices need to be synchronized. Understanding the limits of synchronization in high-density environments will be crucial for future developments.

7.2.2 Enhanced Multipath Propagation Mitigation Techniques

Multipath propagation remains one of the primary challenges in wireless communication, particularly in environments where precision timing is critical. While this thesis proposed techniques to mitigate timing errors due to multipath effects, further research could explore more advanced solutions. Adaptive beamforming techniques, combined with machine learning algorithms, could be used to predict and correct timing errors caused by multipath propagation in real-time.

Additionally, future work could focus on improving the granularity of the synchronization signals themselves, potentially through the use of higher-frequency subcarriers or more sophisticated modulation schemes. These advancements could further enhance synchronization accuracy, making 5G even more suitable for industrial applications that demand high precision.

7.2.3 Energy Efficiency in Synchronization Mechanisms

As the number of connected devices in industrial environments grows, energy efficiency becomes an increasingly important factor. While this thesis focused on achieving high synchronization precision, future research should also consider the energy consumption of the proposed synchronization mechanisms, particularly in IoT and massive Machine Type Communications (mMTC) applications where power resources may be limited.

Investigating energy-efficient synchronization techniques, such as optimizing the power consumption of the TLL circuit or reducing the frequency of synchronization signals without compromising timing accuracy, could significantly improve the sustainability of industrial 5G networks.

7.2.4 Exploring 6G and Beyond

With the development of 6G networks already underway, many of the challenges addressed in this thesis will need to be revisited in the context of the next generation of wireless communication technologies. 6G is expected to offer even higher data rates, lower latency, and more advanced synchronization capabilities. Future research should explore how the synchronization mechanisms developed in this thesis can be adapted or enhanced for 6G systems.

In particular, 6G will likely introduce new frequency bands, such as terahertz (THz) frequencies, which will bring both opportunities and challenges for synchronization. Understanding how the proposed TESC architecture can be adapted to these new technologies will be critical for ensuring that the advancements made in this thesis remain relevant in the future.

7.2.5 Expanding the Applications of TESC

While this thesis focused on industrial applications, the TESC architecture has the potential to be applied in other domains where precise synchronization is critical. Future research could explore how the proposed synchronization mechanisms could be used in areas such as autonomous transportation, smart cities, and telemedicine. These applications also require ultra-reliable, low-latency communication with high synchronization accuracy, making them suitable candidates for the TESC architecture.

7.3 Final Remarks

In conclusion, this thesis has made significant strides in the integration of 5G networks with TSN to support industrial applications that require ultra-precise synchronization. The proposed TESC architecture, combined with the advanced synchronization mechanisms discussed, provides a practical solution for achieving synchronization accuracies of 1 μs or better in real-time industrial environments.

However, as the field of wireless communication continues to evolve, further research and development will be necessary to fully realize the potential of 5G and beyond. By addressing the challenges outlined in this chapter, future work can build upon the foundation laid in this thesis, paving the way for the next generation of time-sensitive networks.

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