

UNIVERSIDAD DE MÁLAGA  
ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA DE TELECOMUNICACIÓN  
PROGRAMA DE DOCTORADO EN INGENIERÍA DE TELECOMUNICACIÓN



TESIS DOCTORAL

LOCATION-AWARE MECHANISMS FOR THE  
MANAGEMENT OF ADVANCED NETWORKS  
INFRASTRUCTURE IN 5G AND BEYOND

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Realizada bajo la tutorización de **Raquel Barco Moreno** y dirección de **Sergio Fortes Rodríguez** y **Raquel Barco Moreno**.

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### CERTIFICAN

Que D. Antonio Tarrías Muñoz, ha realizado en el Departamento de Ingeniería de Comunicaciones de la Universidad de Málaga bajo su dirección, el trabajo de investigación correspondiente a su TESIS DOCTORAL titulada:

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Dicho trabajo ha dado lugar a las siguientes publicaciones en revistas y aportaciones a congresos que no han sido utilizadas en tesis anteriores:

1. **A. Tarrías**, S. Fortes and R. Barco, “Failure Management in 5G RAN: Challenges and Open Research Lines”, in *IEEE Network*, vol. 37, no. 5, pp. 215-222, Sept. 2023.
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4. **Antonio Tarrías**, Sergio Fortes and Raquel Barco, “Failure management insights in 5G using ns-3 network simulation”, *INTERACT 2nd MC and 1st Technical Meetings*, 2022. Bologna, Italy.
5. **Antonio Tarrías**, Alejandro A. Moreno, Francisco Pareja, Eduardo Baena, Raquel Barco and Sergio Fortes. “UE Side Application Layer Metrics for

QoE-Based Network Management”, 2023 *EuCNC & 6G Summit* - Posters. Gothenburg, Sweden.

6. **Tarrías, A.**; Fortes, S.; Baena, E. and Barco, R. “Análisis del efecto del número de beams sobre un escenario 5G” *XXXV Simposium Nacional de la Unión Científica Internacional de Radio (URSI)*, Málaga (Online) 2020
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8. **Tarrías, A.**; Baena, E.; Fortes, S. and Barco, R. “Infraestructura 5G Standalone para Investigación y Desarrollo” *XXXVII Simposium Nacional de la Unión Científica Internacional de Radio (URSI)*, Málaga, 2022

Por todo ello, consideran que esta Tesis es apta para su presentación al Tribunal que ha de juzgarla. Y para que conste a efectos de lo establecido, AUTORIZAN la presentación de esta Tesis en la Universidad de Málaga.

En Málaga, 17 de octubre de 2024

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*To those who stood by me,  
inspired me,  
loved me,  
brought joy to my life,  
selflessly helped me,  
and shaped me into who I am.*



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*“The happiness of your life depends on the quality of your thoughts.”*

Marcus Aurelius

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As I reflect on the journey that led to the completion of this thesis, I am reminded of the Stoic wisdom that we are, in many ways, the products of countless occurrences—both within and beyond our control—that have shaped the course of our lives. It is the combination of these moments, choices, and chance encounters that have brought me here today.

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## Summary of contributions

The various publications resulting from this research are listed below, starting with those that support the thesis.

### Journal articles

- [1] **A. Tarrías**, S. Fortes and R. Barco, “Failure Management in 5G RAN: Challenges and Open Research Lines”, in *IEEE Network*, vol. 37, no. 5, pp. 215-222, Sept. 2023.
- [2] **A. Tarrías**, E. Baena, S. Fortes and R. Barco, “Leveraging 5G SA for R&D: Capabilities and Beam-Based Empirical Analysis”, in *IEEE Open Journal of the Communications Society*, vol. 5, pp. 5608-5618, 2024.
- [3] **A. Tarrías**, I.Hadj-Kacem, G. Bernini, T.E. Kennouche, H.Q. Luo-Chen, M. D. Angelis, A. Margaris, E. Baena, E.J. Khatib, S.B. Jemaa, S. Bartoletti, S. Fortes and R. Barco, “Location-Aware Smart Network Management in Advanced Networks: Design and Applied Proof of Concept”, in *IEEE Network*, Accepted Oct. 2024.
- [4] **A. Tarrías** , A. A. Moreno, F. J. Pareja, E. Baena, S.Fortes, “Towards Zero-Touch Cellular Networks via Next-Generation Crowdsourcing”, *TechRxiv*. March 14, 2023. - *Under Review*
- [5] **A. Tarrías**, S. B. Damsgaard, M. López, T. B. Sørensen, P. E. Mogensen, S. Fortes, R. Barco, “Beam Switching in mmWave 5G: Evaluation in a Realistic Industrial Scenario”, *TechRxiv*, 2024. - *Under Review*

*Additional contributions:*

- [6] C. S. Álvarez-Merino, E. J. Khatib, H. Q. Luo-Chen, **A. Tarrías-Muñoz** and R. B. Moreno, ”Evaluation and Comparison of 5G, WiFi, and Fusion With Incomplete Maps for Indoor Localization,” in *IEEE Access*, vol. 12, pp. 51893-51903, 2024

## International conferences/workshops

- [7] **Antonio Tarrías**, Sergio Fortes and Raquel Barco, “Failure management insights in 5G using ns-3 network simulation”, *INTERACT 2nd MC and 1st Technical Meetings*, 2022. Bologna, Italy.
- [8] **Antonio Tarrías**, Alejandro A. Moreno, Francisco Pareja, Eduardo Baena, Raquel Barco and Sergio Fortes. “UE Side Application Layer Metrics for QoE-Based Network Management”, *2023 EuCNC & 6G Summit - Posters*. Gothenburg, Sweden.

## National conferences/workshops

- [9] **Tarrías, A.**; Fortes, S.; Baena, E. and Barco, R. “Análisis del efecto del número de beams sobre un escenario 5G” *XXXV Simposium Nacional de la Unión Científica Internacional de Radio (URSI)*, Málaga (Online) 2020
- [10] **Tarrías, A.**; Fortes, S.; Baena, E. and Barco, R. “Análisis de Interferencia Cross-Link sobre un escenario 5G mmWave” *XXXVI Simposium Nacional de la Unión Científica Internacional de Radio (URSI)*, Vigo (Online) 2021
- [11] **Tarrías, A.**; Baena, E.; Fortes, S. and Barco, R. “Infraestructura 5G Standalone para Investigación y Desarrollo” *XXXVII Simposium Nacional de la Unión Científica Internacional de Radio (URSI)*, Málaga, 2022

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- [13] Jatib-Khatib, E.; Segura-Ramos, D.; **Tarrías, A.** and Barco, R. “Estudio del ataque de cadena de suministro sobre XZ utils y sus consecuencias en telecomunicaciones” *XXXIV Simposium Nacional de la Unión Científica Internacional de Radio (URSI)*, Cuenca, 2024

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- [14] **Antonio Tarrías**, Eduardo Baena, Sergio Fortes, Raquel Barco, “UE and Network Side Metrics Dataset in Private 5G SA Deployment with Localization and Beamforming Information”, June 17, 2024, *IEEE Dataport*, doi: <https://dx.doi.org/10.21227/302r-w050>.
- [15] **Antonio Tarrías**, Sebastian B. Damsgaard, Melisa López, Troels B. Sørensen, Preben E. Mogensen, Sergio Fortes, Raquel Barco, “5G mmWave Dataset with Beamforming in a Realistic Industrial Scenario”, September 12, 2024, *IEEE Dataport*, doi: <https://dx.doi.org/10.21227/r02m-zx61>.



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## Abstract

Network management has become a key aspect of the cellular network operation. These tasks have gained importance and complexity with each generation of mobile networks. The network management constitutes the basis for the consumers to have a good Quality of Experience (QoE), determining the success of the Mobile Network Operators (MNOs).

Traditionally, the monitoring, analysis, and optimization tasks have been performed by human operators with the help of Operations Support System (OSS) tools. However, the MNOs have devoted resources to automate these tasks, which is known as Self-Organising Networks (SON) techniques: self-configuration, self-optimization and self-healing. The SON techniques aim to reduce the Operational Expenditures (OPEXs) by minimizing the human intervention. In addition, the advent of Machine Learning (ML) techniques has revolutionized the network management, allowing the MNOs to automatically detect, analyze, and even predict network problems.

Moreover, each cellular network generation has brought new challenges to network management. This is due to novel features that introduced new parameters to configure, new Key Performance Indicators (KPIs) to monitor, new network elements to manage, and new services that networks must guarantee. Then, the human effort regarding network management has been redirected to the development of ML-based solutions that can handle the aforementioned aspects.

In this sense, 5G technology has introduced many features to enable new services. This means that new network problems derive from its implementation, and the MNOs must be prepared to face them.

This thesis provides a set of network management mechanisms to address the current 5G and beyond technologies challenges. In particular, it explores the differences with previous generations, identifies emerging problems, and proposes innovative network management techniques from the experimental results based on real-world equipment.

Firstly, it explores the network management paradigm in the 5G era, identifying the main challenges through a literature review as well as a simulation-based analysis. Here, it spots the importance of localization and context information for network management in 5G.

Secondly, it addresses the network management in a real 5G SA deployment. To do that, it deals with the collection of user-side low-layer information, the extraction and definition of novel network-side metrics, and their joint analysis, which create a richer picture of the network status and performance.

Thirdly, it focuses on the exploitation of location information for network management. Here, it proposes a complete framework for the collection, processing, and exploitation of the users' location for a comprehensive network problems detection. In addition, the use of a refined concept of crowdsourcing user-side metrics is considered, based on real data from commercial networks, from a Zero-touch network and Service Management (ZSM) perspective.

Finally, it targets the management optimization of the beamforming technology in 5G-New Radio (NR), considered one of the main novelties of cellular generation. This technology allows the network to steer the signals in several directions, achieving better radio quality for the users. However, it introduces a new mobility challenge for the cellular network: beam management. Then, analysis and evaluation of beamforming have been carried out in a realistic mmWave industrial scenario, proposing variant criteria for the beam switching.

## Resumen

La gestión de red se ha convertido en un aspecto clave del funcionamiento de las redes celulares. Estas tareas han ganado importancia así como complejidad con cada generación de redes móviles. La gestión de red constituye la base para que los clientes puedan tener una buena calidad de experiencia (QoE), lo que determina el éxito de los operadores de redes móviles (MNO).

Tradicionalmente, las tareas de monitoreo, análisis y optimización han sido realizadas por operadores humanos con la ayuda de herramientas del sistema de soporte de operaciones (OSS). Sin embargo, los MNOs han dedicado recursos para automatizar estas tareas, lo que se conoce como técnicas de autoorganización de red (SON): autoconfiguración, autooptimización y auto-sanación. Las técnicas de SON tienen como objetivo reducir los gastos operacionales (OPEX) mediante la minimización de la intervención humana. Además, la llegada de las técnicas de aprendizaje máquina (ML) ha revolucionado la gestión de red, permitiendo a los MNO detectar, analizar e incluso predecir automáticamente problemas de red.

Cada generación de red celular ha añadido nuevos desafíos a la gestión de red. Esto es debido a que las nuevas características introducen nuevos parámetros a configurar, indicadores clave de rendimiento (KPI) a monitorizar, elementos de red a gestionar y servicios que las redes deben garantizar. Por tanto, el esfuerzo humano se ha redirigido al desarrollo de soluciones basadas en ML, que puedan manejar la complejidad de los aspectos mencionados.

En este sentido, la tecnología 5G ha introducido nuevas funcionalidades que permiten nuevos servicios. Esto significa que nuevos problemas de red nacen de dicha implementación, y los MNO deben estar preparados para enfrentarlos.

Esta tesis proporciona un conjunto de mecanismos de gestión de red para abordar los desafíos actuales de las tecnologías 5G y venideras. En particular, explora las diferencias con generaciones anteriores, identifica

problemas emergentes y propone técnicas innovadoras de gestión de red a partir de los resultados experimentales basadas en equipamiento real.

En primer lugar, se explora el paradigma de la gestión de red en la era del 5G, identificando los principales desafíos a través de una revisión de la literatura y un análisis basado en simulación. Aquí, se destaca la importancia de la información de localización y contexto para la gestión de red en 5G.

En segundo lugar, se aborda la gestión de la red sobre un despliegue de red real 5G SA. Para ello, se ocupa de la recolección de información de bajo nivel desde el lado del usuario, la extracción y la definición de nuevas métricas en el lado de la red, y su análisis conjunto, que proporciona una visión más completa del estado y rendimiento de la red.

En tercer lugar, se centra en la explotación de la información de localización para la gestión de la red. Aquí, se propone un marco completo para la recolección, procesamiento y explotación de los datos de localización de los usuarios para una detección integral de problemas de red. Además, se considera un nuevo concepto de métricas del lado del usuario basadas en colaboración abierta distribuida (crowdsourcing), basado en datos reales de redes comerciales, desde una perspectiva de gestión de servicios totalmente automática (ZSM).

Por último, se aborda la optimización en la gestión de la tecnología de conformación de haces (beamforming) en 5G-NR, considerada una de las principales novedades esta generación. Esta tecnología permite a la red orientar las señales en varias direcciones, logrando una mejor calidad radio para los usuarios. No obstante, introduce un nuevo desafío de movilidad para la red: la gestión de los haces (beams). Como consecuencia, se ha realizado un análisis y evaluación del beamforming en un escenario industrial en el espectro milimétrico (mmWave), proponiendo una variante del criterio para el cambio de beam.

# Acronyms

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

**5G** Fifth Generation.

**5GC** 5G Core.

**AAU** Aalborg University.

**AF** Application Function.

**AI** Artificial Intelligence.

**AMF** Access and Mobility Management Function.

**AMR** Autonomous Mobile Robot.

**AoA** Angle of Arrival.

**API** Application Programming interface.

**APN** Access Point Name.

**AUSF** Authentication Server Function.

**BBU** Base Band Unit.

**BFI** Beam Failure Indication.

**BLE** Bluetooth Low Energy.

**BS** Base Station.

**BTS** Base Transceiver Station.

**BW** Bandwidth.

**BWP** BandWidth Part.

**CA** Carrier Aggregation.

**CE** Control Element.

**CG** Cloud Gaming.

**CLI** Command-line Interface.

**CMU** Compact Mobility Unit.

**CN** Core Network.

**COTS** Commercial Off-The-Shelf.

**CPE** Customer Premise Equipment.

**CQI** Channel Quality Indicator.

**CSI** Channel State Information.

**CSI-RS** Channel State Information Reference Signal.

**CU** Central Unit.

**DCI** Downlink Control Information.

**Deep RL** Deep Reinforcement Learning.

**DFT-S** Discrete Fourier Transform-Spread.

**DHCP** Dynamic Host Configuration Protocol.

**DL** Downlink.

**DT** Drive Test.

**DU** Distributed Unit.

**E-UTRAN** Evolved Universal Terrestrial Radio Access Network.

**E2E** End-to-End.

**ECDF** Empirical Cumulative Distribution Function.

**EIRP** Effective Isotropic Radiated Power.

**eMBB** Enhanced Mobile BroadBand.

**eNB** evolved Node B.

**EPC** Evolved Packet Core.

**ETSIT** Superior Technical School of Telecommunication Engineering.

**FR** Frequency Range.

**FTM** Fine Timing Measurement.

**FWA** Fixed Wireless Access.

**GbE** Gigabit Ethernet.

**gCM** Next-Generation Crowdsourcing Metric.

**gCM-M** Mobile Next-Generation Crowdsourcing Metric.

**gCM-S** Stationary Next-Generation Crowdsourcing Metric.

**gNB** Next Generation Node B.

**GNSS** Global Navigation Satellite System.

**GPS** Global Positioning System.

**GUI** Graphical User Interface.

**HARQ** Hybrid Automatic Repeat reQuest.

**HO** Handover.

**IoT** Internet of Things.

**IoT** Internet of Things.

**IP** Internet Protocol.

**ITU** International Telecommunication Union.

**KPI** Key Performance Indicator.

**KQI** Key Quality Indicator.

**LiDAR** Light Detection and Ranging.

**LoS** Line-of-Sight.

**LoS** Line-of-Sight.

**LTE** Long Term Evolution.

**LTE-A** LTE Advanced.

**MAC** Medium Access Control.

**MANO** Management and Orchestration.

**MCC** Mobile Country Code.

**MDT** Minimization of Drive Test.

**MEC** Mobile Edge Computing.

**MIMO** Multiple Input Multiple Output.

**MISO** Multiple Input Single Output.

**ML** Machine Learning.

**mMTC** Massive Machine-Type Communications.

**mmWave** millimetre Wave.

**mmWave** Millimeter Wave spectrum.

**MNC** Mobile Network Code.

**MNO** Mobile Network Operator.

**MU** Multi-User.

**NAS** Non Access Stratum.

**Near-RT** Near-Real Time.

**NEF** Network Exposure Function.

**NF** Network Function.

**NFM-M** Network Functions Manager - Mobile.

**NFV** Network Function Virtualisation.

**NLoS** Non-Line-of-Sight.

**Non-RT** Non-Real Time.

**NR** New Radio.

**NRF** NF Repository Function.

**NSA** Non-Standalone.

**NSSF** Network Slice Selection Function.

**NWDAF** Network Data Analytics Function.

**O-RAN** Open RAN.

**OAM** Operations, Administration and Management.

**OFDM** Orthogonal Frequency Division Multiplexing.

**OPEX** Operational Expenditures.

**OS** Operating System.

**OSS** Operations Support System.

**PCF** Policy Control Function.

**PCI** Physical Cell Identity.

**PDCP** Packet Data Convergence Protocol.

**PDF** Probability Density Function.

**PDSCH** Physical Downlink Shared Channel.

**PHY** PHYsical layer.

**PM** Performance Management parameter.

**PMI** Precoding Matrix Indicator.

**PoC** Proof of Concept.

**PRACH** Physical Random Access Channel.

**pRRH** pico Remote Radio Head.

**PRS** Positioning Reference Signal.

**PSS** Primary Synchronization Signal.

**QoE** Quality of Experience.

**QoS** Quality of Service.

**R&D** Research & Development.

**RA** Random Access.

**RACH** Random Access Channel.

**RAN** Radio Access Network.

**rApp** RAN Application.

**RAT** Radio Access Technology.

**RF** Random Forest.

**RI** Rank Indicator.

**RIC** Radio Intelligent Controller.

**RLC** Radio Link Control.

**RLF** Radio Link Failure.

**RLM** Radio Link Monitoring.

**RLQ** Radio Link Quality.

**RRC** Radio Resource Control.

**RRH** Radio Remote Head.

- RS** Reference Signal.
- RSRP** Reference Signal Received Power.
- RSRQ** Reference Signal Received Quality.
- RT** Real-Time.
- RTT** Round Trip Time.
- RU** Radio Unit.
- SA** Standalone.
- SBA** Service Based Architecture.
- SBSR** Specific Beam Switching Ratio.
- SCAT** Signaling Collection and Analysis Tool.
- SCS** SubCarrier Spacing.
- SDK** Software Development Kit.
- SFF** Small Form Factor.
- SIMO** Single Input Multiple Output.
- SINR** Signal-to-Interference-plus-Noise Ratio.
- SLAM** Simultaneous Localization And Mapping.
- SMF** Session Management Function.
- SMO** Service Management Orchestration.
- SNR** Signal-to-Noise-Ratio.
- SON** Self-Organising Networks.
- SQL** Structured Query Language.
- SRS** Sounding Reference Signal.
- SS** Synchronization Signal.
- SSB** Synchronization Signal Block.

**SSS** Secondary Synchronization Signal.

**SU** Single-User.

**TDD** Time Division Duplex.

**ToA** Time-of-Arrival.

**ToS** Time of Stay.

**TS** Technical Specification.

**TTT** Time-to-Trigger.

**UC** Use Case.

**UDM** Unified Data Management.

**UE** User Equipment.

**UEXM** UE Cross Movement.

**UL** Uplink.

**UMA** University of Malaga.

**UMTS** Universal Mobile Telecommunications System.

**UPF** User Plane Function.

**URLLC** Ultra Reliable Low Latency Communications.

**UWB** Ultra-Wide Band.

**VNF** Virtual Network Function.

**VR** Virtual Reality.

**xApp** eXtended Application.

**XR** Extended Reality.

**ZSM** Zero-touch network and Service Management.

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# Part I

## Background

# Chapter 1

## Introduction

### Content

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The aim of this first chapter is to expose the motivation and the purpose of this thesis, to present the objectives and to describe the organization of this document.

## 1.1 Motivation

The advent of cellular networks revolutionized the way people communicate, work, and live. It enabled ubiquitous and always-on connectivity that has changed people's way of living, from the social interactions to the economic aspects of society. This has been possible thanks to the continuous evolution of mobile networks and their deployment in a vast majority of the world.

However, each new generation of cellular networks has brought new challenges, opportunities, and requirements. It started with voice calls, then it evolved to data services, and it is currently achieving extremely complex services as Extended Reality (XR), Cloud Gaming (CG) or autonomous driving. From the economic perspective, it has enabled key features for businesses, such as e-commerce platforms, cloud services, Internet of Things (IoT) or Industry 4.0. Nevertheless, each generation of the cellular network technology has implied a significant effort for the Mobile Network Operators (MNOs) to deploy the new infrastructure elements and to adapt the physical scenarios, e.g., to install new sites to provide the required coverage and capacity for the new Use Cases (UCs) in almost the same areas where they deployed the previous generation. Notwithstanding, the global mobile service revenue has grown around 15% in the last 3 years [18].

The importance of cellular networks is stated by the reports about traffic usage, where there is an exponential growth of the consumed data traffic by the users. The total mobile data traffic has increased from 10 EB in Q1 2017 to 145 EB in Q1 2024, including DL and UL traffic [19]. This growth is driven by increasing both the number of subscriptions and the average data usage per subscription. In addition, the adoption of each new generation is faster than the previous one. The 5G-New Radio (NR) specification was completed by 3rd Generation Partnership Project (3GPP) in 2017, and the number of 5G subscriptions has remarkably increased since then, adding 160 million 5G subscriptions during the first quarter of 2024 to exceed a total of 1.7 billion [19]. Here, the 5G subscriptions are counted when devices that support NR, as specified in 3GPP Release 15, are connected to a 5G-enabled network. The number of 5G subscriptions is set to reach nearly 5.6 million in 2029 [19].

In this sense, the rise of users, the emergence of new demanding UCs, and the heterogeneity of the scenarios have been in the spotlight from a network management perspective. Network management is a key aspect for the MNOs to

ensure service quality and to provide a seamless user experience. The automation of the Operations, Administration and Management (OAM) tasks has led to the development of the Self-Organising Networks (SON) concept, which was first defined in 2008 [20]. The SON paradigm includes self-configuration, self-optimization, and self-healing functionalities, which are aimed at reducing operational costs and improving network performance. Due to this fact, the literature on this topic is extensive [21, 22, 23, 24, 25].

Nevertheless, the 5G technology introduces new features, such as new frequency bands, beamforming, higher bandwidth allocation, the use of TDD, and new network architectural components, among others. The aforementioned features introduce a new dimension of parameters that can be configured, making network management more complex.

The classical OAM systems are based on network information, i.e., KPIs and counters that are collected from the network elements at low periodicity (e.g., 1 hour or 15 minutes at most). This means that the reactivity of the network management is limited, and the network perspective is also limited.

For this reason, there are additional sources of information, such as the localization information [26, 27, 28, 29] and the context information [30, 31], that have become crucial for the network OAM, as they provide additional information to the OAM systems to make well-founded decisions. The context information includes external aspects, e.g., social events [32], that may enrich the network management view. Also, the user-side metrics collection is envisioned as an additional source of information to consider for network management, as it provides direct feedback on the user experience [33, 34, 35]. This concept may replace the expensive Drive Tests (DTs) that have been traditionally performed by the MNOs to evaluate the network and find problems.

In this context, the use of Machine Learning (ML) techniques unlocks the potential to handle a large amount of configurable parameters altogether. The ML algorithms are used for multiple purposes in the literature: self-organizing 5G networks with Deep Learning [36], root-cause analysis [37], cell fault management [38], or self-healing management in ultra-dense networks [30].

Therefore, the previous considerations open a wide range of research opportunities based on the novel 5G features, the new sources of information, and the ML techniques, together with the more exigent user requirements and the need

for a network flexibility and adaptability to the new UCs. Then, this thesis develops novel approaches to fulfill the described needs, and it is focused on enhancements that can be applied in the context of 5G and beyond networks, where the O-RAN paradigm [39, 40] is envisaged as a further step of the network evolution based on open-source software and multivendor hardware interoperability.

## 1.2 Preliminaries

This thesis was carried out at the Mobile Networks Lab research group (*MOBILENET*), belonging to the University Institute of Telecommunications (*TELMA, TIC-102*) of the University of Malaga.

The *MOBILENET* group came into existence as the result of the collaboration between the TIC-102 group and Nokia Networks in the creation of the Mobile Communications Research Centre in the Andalusia Technology Park (PTA) in Málaga, in 2000. This unit consisted of more than 50 people, including professors from the University of Malaga and experienced staff from Nokia.

Thus, *MOBILENET* started working in the research and development of SON algorithms for mobile networks. In this respect, one of the first projects undertaken by the group, in collaboration with Nokia Networks, was the development of an automated RAN problem-solving tool. This laid some foundations for fusing real mobile network data and engineering expertise into an automated troubleshooting tool. Later, this idea has been enriched with the application of ML techniques to the existing tools, making them more powerful.

Since the beginning, the research group has been part of consortia with national and international companies in the framework of several research projects. Among the most recent is the *H2020 LOCUS* project, focused on the collection, analysis and application of localization information towards network management, where part of this thesis has been developed.

The research of *MOBILENET* is conducted within the University of Malaga [41]. This allowed experimental tests to be carried out on a private 5G SA network, made up of 6 indoor pico Remote Radio Heads (pRRHs), 3 outdoor cells, and a virtualized complete 5G Core (5GC). This infrastructure is composed of commercial equipment and completely isolated from commercial networks, which allows to make

any configuration change without requesting any permission.

## 1.3 Challenges and objectives

The main objective of the thesis is to propose novel network management mechanisms for 5G technology and beyond. In particular, they will address the newly introduced challenges that are derived from the introduction of novel features to support the innovative Use Cases (UCs). Similarly, this work aims to extend the automation of cellular network to the next level, being able to support the last and following generations of cellular networks.

The cellular network scenarios have evolved significantly in recent years, driven by the introduction of new services and the need to support a wide range of devices. This has led to the development of new network architectures and technologies that are more flexible and adaptable to the requirements of the services. Figure 1.1 sketches a heterogeneous 5G scenario. In this scenario, there are two Radio Access Technologys (RATs) that coexist: Long Term Evolution (LTE) and 5G. In the latter case, there are different types of cells, the classic urban macro cells, usually sited in rooftops or high locations, but also the new Millimeter Wave spectrum (mmWave) cells, which are located in street furniture, as their coverage footprints is limited. In addition, there are users demanding the three main UCs: Enhanced Mobile BroadBand (eMBB) (e.g., subscribers performing demanding tasks in terms of data rates), Massive Machine-Type Communications (mMTC) (e.g., sensors) and Ultra Reliable Low Latency Communications (URLLC) (e.g., connected vehicles). Besides, a subset of potential network problems that may occur in the depicted scenario are illustrated, such as the interference between cells, the beam failure, or a lack of capacity due to a cluster of people demanding services in a specific area.

As observed in the figure, network management is becoming more complex and challenging due to the increasing number of dimensions that need to be considered, from parameters that can be configured, new network elements implementing novel features, and new services offered.

In this context, a comprehensive analysis of the 5G cellular technology is the first step to understand the changes with respect to the previous generations, as well as to understand the novel features that are introduced in 5G (Objective 1). Thus, this task will allow the identification of the main causes of RAN problems, as

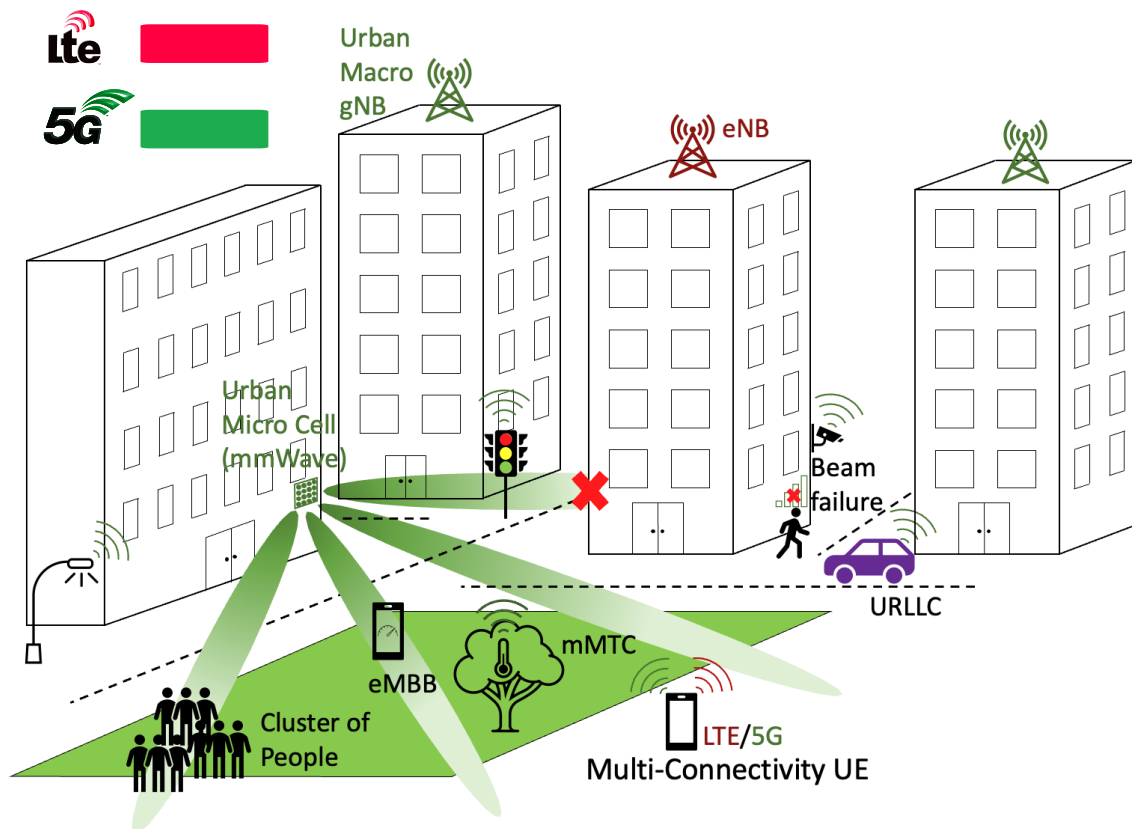


Figure 1.1: 5G Heterogeneous Scenario.

well as the classic network problems that have been present in previous generations, e.g., mobility management. This analysis encompasses the analysis under simulation tools and an in-depth understanding of the 3GPP specifications. The output of this task is the identification of candidate problems that may occur in the network, those where the current network management solutions are not ready to address them.

Once the candidate problems are verified under simulation, the proposal of innovative techniques to address them in the case of occurrence constitutes the second objective of this thesis (Objective 2). In particular, the beamforming technology is considered an additional layer of complexity regarding mobility management, so the beamforming management procedures become a subject of study. Additionally, given the new exigent requirement of the cellular network in terms of UCs, the network-side metrics are not enough to ensure service quality. Then, the exploitation of user-side metrics (Objective 2.1) and localization information (Objective 2.2) for network management is evaluated.

The performance analysis of the proposed techniques on real deployments is also a key objective of this thesis (Objective 3), incurring the complexity of working with

real equipment but providing added value to the achieved outcomes.

Finally, the integration of the previous objectives into a network management framework aims at providing a tested and ready-to-use solution to the network management challenges that are derived from the introduction of 5G technology (Objective 4).

In this way, the primary objectives of the thesis are summarized as follows:

- **Objective 1:** To explore and thoroughly analyze the novel aspects of the 5G technology, focusing on the RAN and the services that are provided over it. This objective paves the way towards the identification of the main network problems that are preliminarily evaluated.
- **Objective 2:** To propose innovative techniques to address the novel features and identified network problems introduced in 5G, with a special focus on beamforming technology. Due to the increased complexity of the network, the use of two additional sources of information is considered:
  - **Objective 2.1:** To exploit the user-side metrics that provide a richer perspective of the real performance that the users are experiencing. This will enable the identification of the main factors that affect the Quality of Experience (QoE) of the service.
  - **Objective 2.2:** To benefit from the integration of localization information regarding network management. This will provide a more accurate view of the network, allowing the identification of candidate areas where problems may occur and assisting the mobility management procedures, especially regarding beamforming.
- **Objective 3:** To analyze the performance of the proposed techniques as well as beamforming implementation in real deployments.
- **Objective 4:** To develop a framework integrating the proposed techniques, which includes the exploitation of user-side metrics and localization information for network management purposes.

Notwithstanding, there is a transversal objective that has been part of the work during the development of this thesis: the deployment of real infrastructure. During the thesis, the project of deployment of real equipment has been led, considering

not only the technical part but the coordination of different entities at University of Malaga (UMA), the decision about the location cell sites, and the continuous interaction with both the MNO and the equipment vendor. This equipment has been later used for the development of the thesis, as well as for other research activities, including European projects, and by more than 30 researchers from the *MOBILENET* group.

Finally, a summary of the research carried out in the context of this thesis is presented.

Figure 1.2 provides an overview of the relationship between the challenges and objectives covered in the realm of this thesis.

The challenges are defined as the main problems that were initially identified in the realm of the thesis. Once the challenges were identified, a set of objectives were defined to address the challenges. These objectives are achieved by a set of contributions in the form of journal papers. The compilation of the papers covers the defined objectives.

## 1.4 Research Methodology

The methodology is a fundamental pillar of the research. In this work, a research methodology has been used to guide the process, including the following steps.

1. **Identification of research gaps.** The first step consists of a comprehensive literature review related to the topic under consideration. This helps to analyze the relevant areas in need of solutions or improvements, thus identifying the main challenges that have not yet been addressed in the literature. A basis of technical knowledge is required. It is important not only to review the literature but also to actively engage and collaborate with leading companies through research projects. This step is tackled as the first objective of the thesis (See 1.2).
2. **Problem statement.** Once the challenges are identified, it is important to concrete the problem. This implies discarding all the unrelated aspects for the problem and creating a clear definition of the problem. It also includes the technical aspects of the problem and the criteria for success. This step is also covered by the first objective of the thesis (See 1.2).

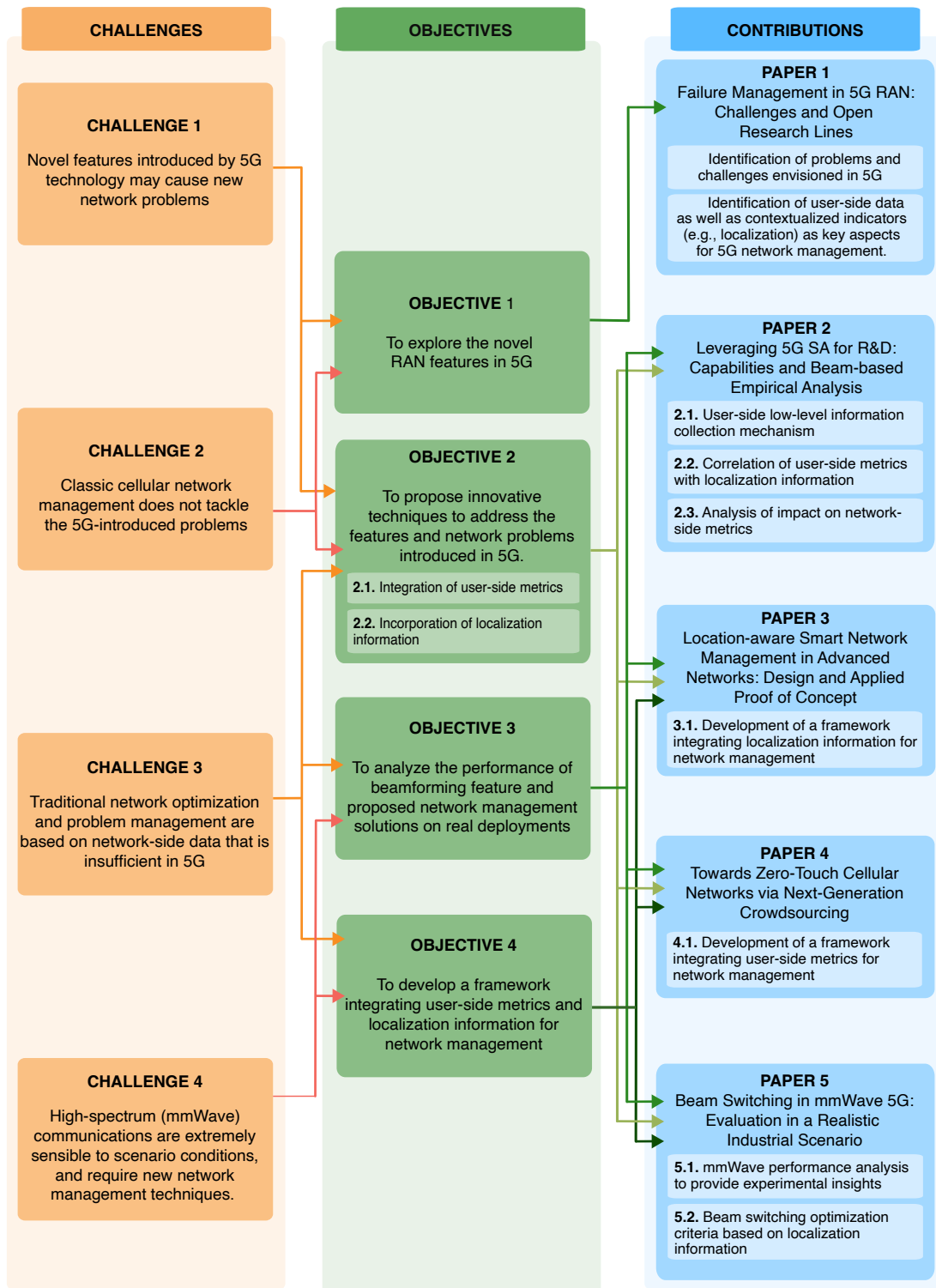


Figure 1.2: Challenges, objectives and contributions

3. **Solution design and implementation.** The third step consists of proposing an approach to solve the problem. This is the most complicated step, as it requires a deep understanding of the problem and the state of the art,

and proposing a different or refined solution is not trivial. Limitations may appear during the development of the solution, and the process may need to be adapted. This process may require the collection of data, the development of algorithms, the implementation of several components, or the integration of different technologies, among others. This is partially covered by both Objectives 2 and 4.

#### 4. **Evaluation of the proposal.**

The performance evaluation is a crucial step in the research process. A solution may not achieve proper performance, so it may be necessary to iterate between this and the last step. In this thesis, evaluation is initially addressed by the use of simulation tools, but mostly using real equipment and data from real commercial networks, which makes the result more reliable. The effectiveness of the solution is measured by the defined criteria in the second step. During this process, the solution is carefully tested under different conditions. The evaluation is part of both Objectives 3 and 4 of this thesis.

5. **Dissemination.** The publication of results and participation on different activities is a fundamental aspect of the research process. It is important to share the results with the scientific community and to receive feedback from other researchers. This way, the proposed solutions can be adapted, improved, or even refuted. Here, it is important to clearly state the major insights and contributions of the research, and the representation part also plays a crucial role. Regarding this thesis, the research activities are included in Section 6.3.

## 1.5 Document structure

The manuscript of this thesis is divided into three parts: background, development and experimental process, and achievements. The manuscript is also structured in six chapters, containing detailed descriptions of each part. This distribution is depicted in Figure 1.3.

### Part I - Background

The first part of the document includes the motivation for this thesis as well as the technical background that is needed for the sake of properly understanding

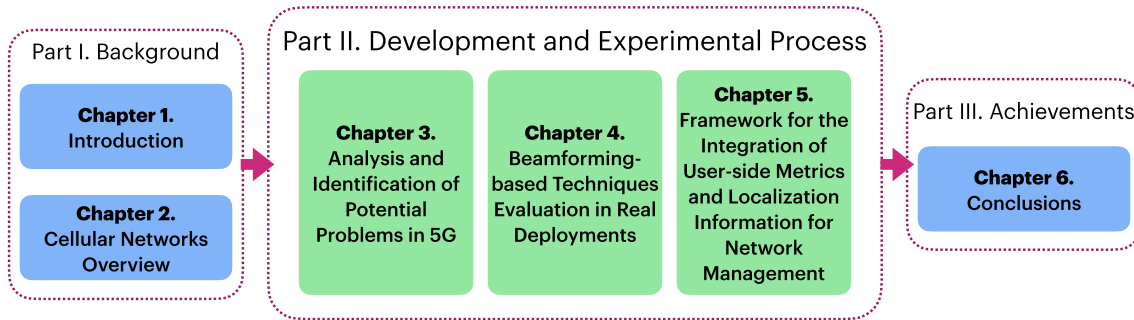


Figure 1.3: Document structure

the content of this work. Chapter 1 presents the motivation, preliminaries, and challenges and objectives of this thesis. Then, Chapter 2 describes the theoretical concepts as well as a technical introduction to the topics that are further developed in this work. In particular, it encompasses cellular networks, including the current 5G and O-RAN, and also network management, with special focus on mobility management and beamforming.

## Part II - Development and Experimental Process

The second part constitutes the core of the dissertation.

Chapter 3 address the initial part of the technical work, where an initial analysis is carried out on the current status of 5G technology, standardization aspects, and the main potential network problems that are identified.

Chapter 4 is focused on the beamforming technology. Concretely, the content of this chapter encompasses two parts: the analysis of capabilities a real outdoor network deployment, where the network performance is evaluated by comparing both network and user side; and the study of beam switching at mmWave in an industrial indoor scenario, including refined criteria to enhance the beam switching.

Chapter 5 consists of the development of a framework that integrates the proposed techniques. These techniques comprise the exploitation of user-side metrics and localization information for network management. This framework is tested with data from real commercial users as well as privately in real controlled environments.

## **Part III - Achievements**

The third part outlines the Chapter 6, which contains the main outcomes and conclusions of this thesis. It also enumerates future research directions that can be pursued based on the results obtained from the work performed. Finally, Chapter 6.3 describes the dissemination activities, projects, and the research stay conducted in the context of the thesis.

## **Appendices**

This document includes a summary of the thesis in Spanish in the Appendix A.



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# Chapter 2

## Technical Background

### Content

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This section describes the fundamental technical concepts for the sake of understanding the content presented in the remaining of this thesis.

In this regard, Section 2.1 introduces the basic concepts of mobile networks, Sections 2.2 and 2.3 present the main characteristics of the latest advancements related to them, respectively. Finally, Section 2.4 presents the relevant aspects of network management, with a special focus in mobility management.

## 2.1 Cellular networks

Cellular networks, also called mobile networks, constitute one of the most relevant technologies of the modern society. They provide ubiquitous connectivity to users and devices, becoming one of the pillar of the digital transformation. They constitute the basis of a wide range of services, from communications to economic transactions, without forgetting the entertainment and social networks.

The adjective cellular comes from the idea that the network architecture is composed by different base stations that are strategically sited on a territory, where each base station provides coverage to a cell, creating a grid which aims to cover the 100% of the territory. The main characteristic of these networks is the ability to provide continuous connectivity to users while they are moving, allowing them to maintain the connection without interruptions, thanks to the implementation of a handover process between cells.

Here, the 3rd Generation Partnership Project (3GPP) is the organization responsible for the standardization of cellular networks. This organization is composed by an extensive range of companies and institutions that work together to define the characteristics and capabilities of the network, including the most technical aspects related to protocol implementation and architecture components. The 3GPP is in charge of publishing different releases. Each release contains a set of technical specifications that details all the aspects of the network, from the radio interface to the core network. Then, the manufacturers need to be compliant with these specifications to ensure the interoperability between the different vendors, meaning that any UE must be able to connect to any cellular network if they are compliant with the same release. Thus, each cellular network generation is related to a set of 3GPP releases, which also define the performance requirements expected to be achieved by a specific generation.

Although there are differences between cellular network generations, they present three distinctive parts, as illustrated in Fig. 2.1: UE, RAN and Core Network (CN).

Firstly, the CN is the wired part of the network, where all the functions are allocated, including the databases, authentication servers, accounting servers, mobility management components, and the gateways to Internet. It is in charge of routing the data between the different users, cells and networks. Moreover, additional capabilities are being added to the CN to implement ML functionalities,

and therefore achieving a more complex and efficient OAM. In the same way, there is a tendency to implement the Network Function Virtualisation (NFV), which consists of having the different network functions running on virtual machines in a single hardware, reducing the costs and increasing the flexibility of the network.

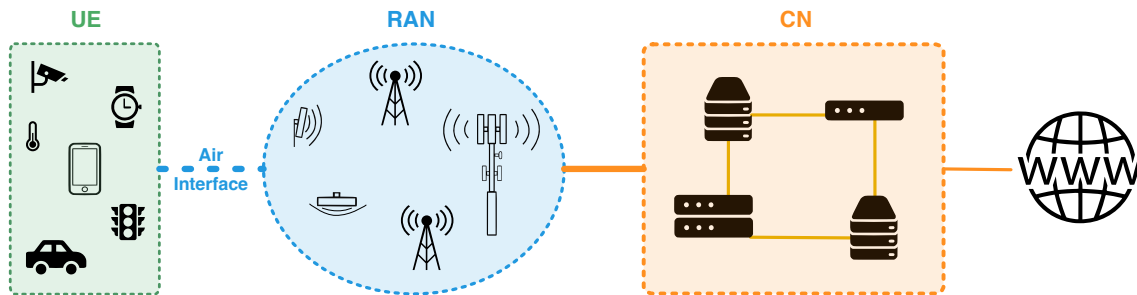


Figure 2.1: Simplified Architecture of Cellular Networks.

On the other hand, the RAN implements the wireless part of the network, enabling the communication between the radio interface with the UEs. The link from the RAN to the CN is based on high-speed wired links, usually optical fibers, to ensure the high data rates and negligible latency on this part of the network. The Base Stations (BSs) (also named cells) are part of the RAN, and they radiate the different signals to the users. These signals are defined by the 3GPP specifications, and they can be always-on transmissions, or scheduled transmissions based on the user demand. They are divided into different logical and physical channels, where each one contains a specific type of information, such as control information, user data, or synchronization signals. In addition, the BSs must seamlessly manage the movement of the users, and trigger the handover procedure when specific conditions are met. The RAN also manages the radio resources, which means that it allocates different parts of the spectrum to the different users, but it also needs to deal with the interference between different cells.

Finally, the UE encompasses the different types of devices that can connect to the network, including smartphones, tablets, wearables, vehicles, and IoT appliances.

The communication between these three parts is based on a set of protocols which are specified by the 3GPP. The protocol stack has been slightly adapted between the different generations, but the main structure is maintained. The structure of the protocol stack is depicted in Fig. 2.2. Although specific acronyms name the protocols, they are usually grouped into Layer 1, Layer 2, and Layer 3, as indicated in the figure. From top to bottom, each information is encapsulated in the next protocol layer. The legend in the bottom left part of the figure indicates what are

the protocols used for: control, user data, or both. The horizontal lines and dashed boxes illustrate the parts between each protocol is used: UE, RAN, and CN. The functionality of each layer is the following:

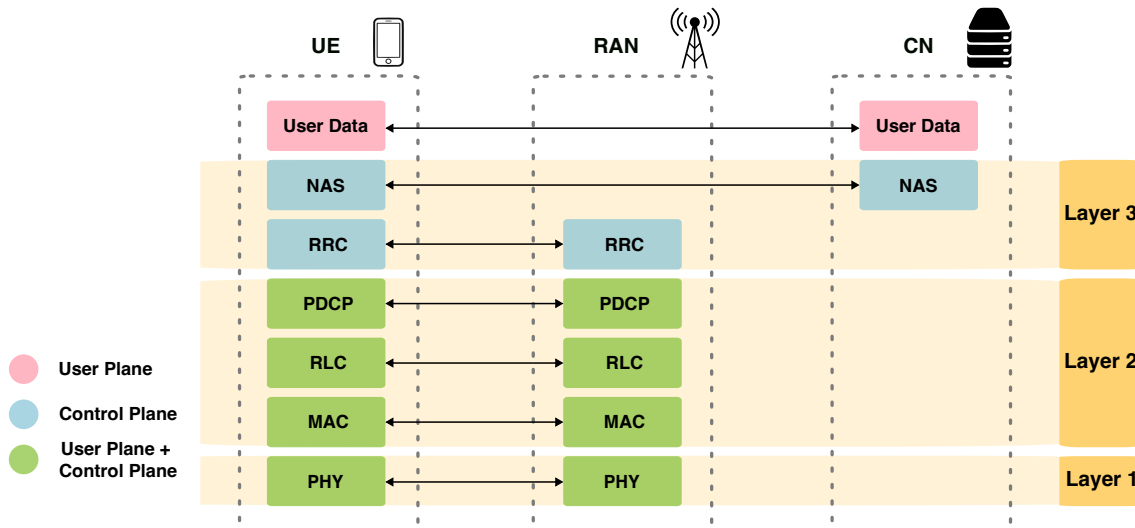


Figure 2.2: Protocol stack

- Non Access Stratum (NAS). It is in charge of signalling between the UE and the CN to manage the session, including establishment, modification and release of the connection. It is also involved in the inter-cell handover procedure, as the UE needs to inform the network about the change of cell, but not in the intra-cell handover and neither in the beam switching procedure in 5G networks.
- Radio Resource Control (RRC). This protocol handles the communication between the UE and the RAN, so it is involved several procedures, such as the connection establishment, reconfiguration, handovers, and connection release. Radio Resource Control (RRC) acts as a control center for all the lower layers within each system, then its main function is to configure the radio resources, i.e., the Packet Data Convergence Protocol (PDCP), Radio Link Control (RLC), MAC, and PHYSical layer (PHY) layers. Then, RRC is purely dedicated to signalling and control, and it implements the following states: idle, inactive (introduced in 5G) and connected.
- Packet Data Convergence Protocol (PDCP). This layer is responsible for packet encryption, header compression, sequential delivery, duplicate discard at re-establishment of lower layers, and integrity protection.

- RLC. This protocol transfers packets from the PDCP layer using one of the three defined modes: transparent mode (TM), unacknowledged mode (UM), and acknowledged mode (AM). It performs error correction in AM mode, and segmentation and reassembly in AM and UM mode.
- Medium Access Control (MAC). It manages the mapping of logical channels to transport channels, scheduling, error correction through Hybrid Automatic Repeat reQuest (HARQ) (consisting on retransmitting the erroneous parts), and multiplexing of data.
- PHYsical layer (PHY). The PHY governs the transmission and reception of the radio signals, including modulation, numerology, coding, multiple access schemes, beamforming, and Multiple Input Multiple Output (MIMO). It also measures the radio channel quality and reports it to the upper layers (e.g., Channel Quality Indicator (CQI)).

The described protocol stack has remained almost the same between the different generations of cellular networks. However, each new generation has introduced new features and functions to the defined protocols, e.g., the novel RRC inactive state, or the beamforming capabilities and new frame structure in the PHY layer that are used in 5G.

These protocols are defined by 3GPP through different Technical Specification (TS) documents. This ensures the interoperability between network vendors and UE manufacturers, although there are some aspects that are left to the vendors for implementation, such as the handover algorithms, i.e., which conditions and thresholds are used to trigger the handover procedure.

Then, the following subsection targets the current and immediate future cellular network generation details, including the architecture and main characteristics.

## 2.2 5G

The Fifth Generation (5G) is the latest generation of cellular networks that has been deployed worldwide. However, it has inherited from LTE in a wide range of aspects, introducing new features and capabilities to the network. Firstly, for the sake of understanding, it is important to introduce the three main parts, as described in the previous section: CN, that has been renamed from Evolved Packet

Core (EPC) (LTE) to 5GC; the RAN, now called 5G-NR while it was previously known as Evolved Universal Terrestrial Radio Access Network (E-UTRAN) (LTE), which in turn proceeds from UTRAN (Universal Mobile Telecommunications System (UMTS)/3G); and UE. Likewise, the base stations have been renamed from evolved Node B (eNB) to Next Generation Node B (gNB).

The NR was defined and developed in the first place, being functionally frozen in June 2018 and fully specified by September 2019, following three design principles [42]:

- **Flexibility:** to adapt to different use cases and scenarios, that will be described below, but also a wide range of carrier frequencies, including: Frequency Range (FR)1 (also known as sub-6 GHz); and FR2 (also known as mmWave).
- **Forward Compatibility:** to coexist with the previous generations, i.e., LTE, but also be prepared for future generations, e.g., supporting different types of frame structures even if some of them are not defined yet.
- **Ultra-lean Design:** to minimize the energy consumption from various perspectives, e.g., the minimization of “always-on” transmissions on the PHY layer, but without compromising the compatibility with the future generations or the compatibility of user devices.

Nevertheless, while the main purpose of developing LTE was to solve the identified problems from UMTS as well as to achieve higher data rates and capacity, the main goal of building 5G was to provide UCs based network, to offer a wide variety of services of different nature. Unlike UMTS, LTE had proved to be a successful technology, and there were advancements as the Carrier Aggregation (CA) evolution in LTE Advanced (LTE-A), that enhanced the initial objective of reaching higher data rates.

In this sense, 5G aimed to support three main UCs [16]:

- **eMBB:** to provide higher data rates and capacity in order to enable exigent applications such as high definition video streaming or Virtual Reality (VR). The mmWave range is particularly suitable for this aim due to the large bandwidth available, but it is also limited in terms of coverage.

- **URLLC**: to support applications that require communication to be almost real-time with close to zero packet loss, such as industrial automation, autonomous vehicles, or remote surgery.
- **mMTC**: to enable the connection of a huge number of devices simultaneously. These devices usually make a low use of the network resources, but prioritizes a low energy consumption as well, such as sensors, actuators, or wearables.

However, there are many UCs that are in the middle of these three main categories, e.g., an application requiring a high reliability but not necessarily a low latency. Figure 2.3 illustrates different applications and services that are envisioned to be supported by 5G.

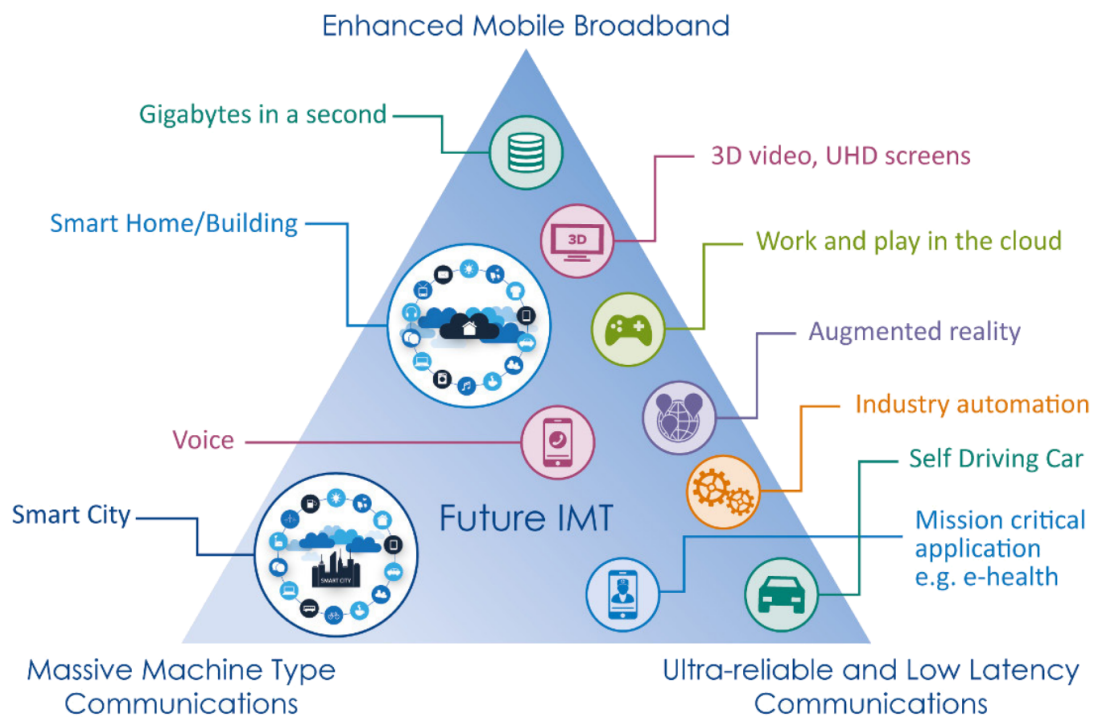


Figure 2.3: Use Cases (UCs) in 5G [16].

### 2.2.1 Architecture

As mentioned in the previous section (Sec. 2.2), 5G was developed from the well proven LTE. In this sense, two possible operation modes were defined: Non-Standalone (NSA) and SA. From the architectural point of view, 5G NSA utilizes uniquely the EPC from LTE, and only and updated additional RAN based

on NR is added to the existing E-UTRAN. In contrast, 5G SA implements a completely new architecture, 5GC, and removes the E-UTRAN to make exclusive use of the 5G-NR. Figure 2.4 illustrates the differences between these two operation modes, where the dashed lines represent the NSA mode, and the solid lines the SA mode. It is important to note that control plane is always sent through LTE in the NSA mode, while the NR is only used for the user plane.

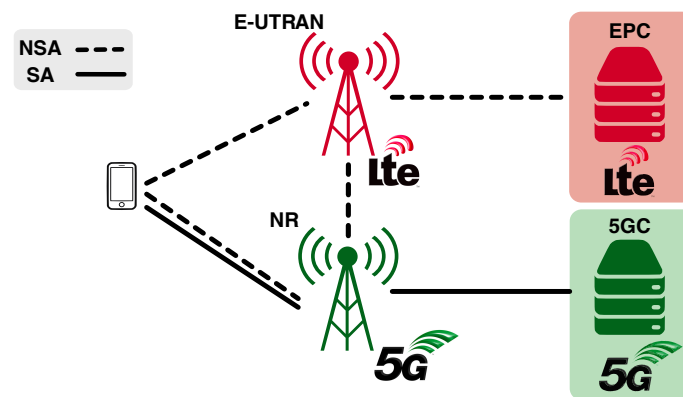


Figure 2.4: 5G Standalone (SA) and Non-Standalone (NSA) Modes.

In addition, the architecture of the 5GC has been improved from the EPC, so that there are LTE EPC functions that can be directly mapped to 5GC functions (See Fig. 2.5). Although, EPC elements are not utilized to operate 5G SA. Moreover, the novel design of the 5GC, concretely the control plane, is based on a new paradigm known as Service Based Architecture (SBA), that aims to provide a more flexible and scalable network, where the different functions are implemented as Network Functions (NFs) that can be deployed in different locations if necessary. Figure 2.5 depicts the CN architecture, where the 5GC components are represented in green, and EPC components are in red. Also, the interfaces, also named reference points, between the components are included in the figure, e.g., N2 is the control plane interface between the RAN and the 5GC (Access and Mobility Management Function (AMF)).

The main 5GC components are the following:

- Access and Mobility Management Function (AMF): It handles registration management, connection management, mobility management, authentication, and authorization. The Non Access Stratum (NAS) signalling from the UE (See Fig. 2.2) is terminated in the AMF.
- Session Management Function (SMF): It manages the sessions, Dynamic Host

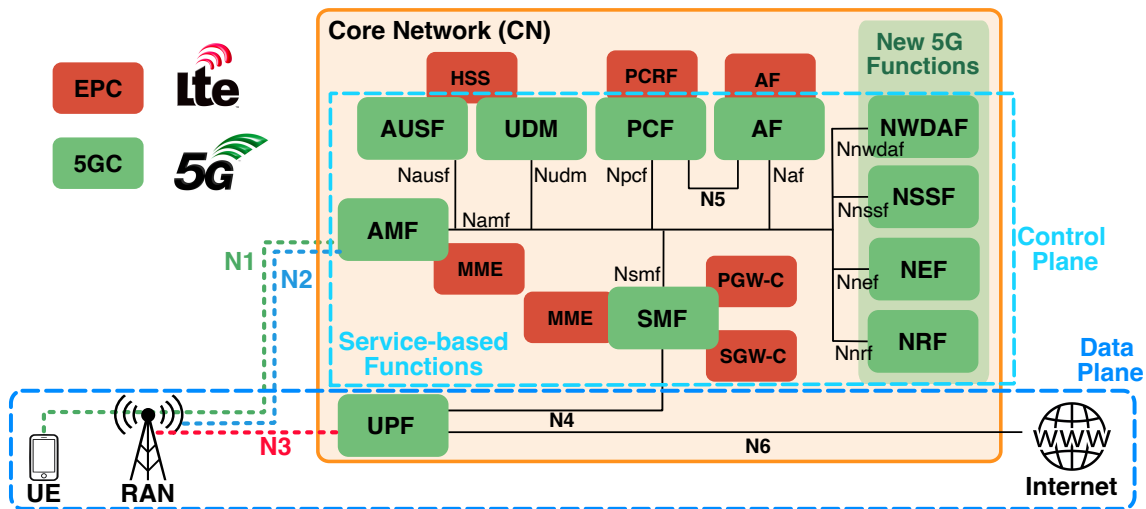


Figure 2.5: Core Network Architecture.

Configuration Protocol (DHCP) and Internet Protocol (IP) address allocation, data and traffic management.

- User Plane Function (UPF): It controls packet handling and QoS management, and acts as the gateway to the Internet. It participates in the intra- and inter-RAT handover procedures. The User Plane Function (UPF) instances are clear candidates to be flexibly deployed in multiple locations upon the network requirements, e.g., it must be deployed very close to the end users for latency sensitive applications (URLLC), or in a far location for mMTC applications with more relaxed latency requirements.
- Unified Data Management (UDM): It stores the user data of subscribers.
- Authentication Server Function (AUSF): It works in conjunction with the Unified Data Management (UDM) to authenticate the users.
- Policy Control Function (PCF): It administers the policy control and management, with additional capabilities to monitor the QoS.
- Application Function (AF): It is responsible for traffic management, QoS assignment, and provision of services to subscribers.
- Network Data Analytics Function (NWDAF): It processes the network data from several sources within the network to provide the network functions with useful information to make proper decisions.

- Network Slice Selection Function (NSSF): It considers the slice availability and check the policies with the Policy Control Function (PCF) to manage the slices instances that serve the users.
- Network Exposure Function (NEF): It enables the discovery of network functions across the network.
- NF Repository Function (NRF): It is designed to allow the network functions to offer their services to other network functions by acting as a catalog. This component enables the use of ML techniques to improve the network operation.

### 2.2.2 New Radio (NR)

One key element of the exponential growth of the cellular networks' usage is the efficient use of radio spectrum. The NR has been redesigned to provide a more flexible and high performing radio interface. The aspirational capabilities of the NR are driven by the need to support UCs of different nature. Satisfying the aforementioned three main UCs (eMBB, URLLC, mMTC) in isolation is challenging, but doing so simultaneously gets even more complex. Due to this fact, RAN aspects have been built up from the lower layers with this aim.

Firstly, the frequency bands in NR span from 0.41 GHz to 52.6 GHz [43]. The lower frequencies are suitable for providing coverage to a wide area, while the higher frequencies are more adequate for high data rates and capacity. The higher frequencies are also known as mmWave. They are particularly sensible to obstacles and suffer high propagation losses, but they offer a large bandwidth that can be used to achieve higher data rates and capacity, as the spectrum availability increases at that frequency. This means that wider contiguous blocks of spectrum can accommodate a single 5G carrier with a higher bandwidth, what enables a simpler management of the spectrum. Carriers of up to 100 MHz are supported for FR1, and up to 400 MHz for FR2, meaning that the effect of guard bands overhead is minimized, and therefore improving the spectral efficiency. Additionally, the higher frequency the smaller the wavelength, which allows the use of smaller antennas, and therefore the implementation of MIMO and beamforming technologies, that will be described in detail in the following sections.

Regarding the waveform, 5G uses Orthogonal Frequency Division Multiplexing (OFDM) for both DL and UL, although Discrete Fourier Transform-Spread (DFT-

S)-OFDM can be enabled for UL upon activation at RRC layer to achieve a better UL coverage.

Besides, NR introduces numerologies, which means flexible SubCarrier Spacing (SCS). While 15 kHz was the unique SCS in LTE, NR supports 15 kHz, 30 kHz, 60 kHz, 120kHz, 240 kHz, 480 kHz, and 960 kHz SCS (Release 17). When the SCS increases, the symbol duration must be reduced to maintain orthogonality between subcarriers. However, the selection of the SCS depends on the frequency band, as the shorter symbols can be used at higher frequencies due to the less significant delay spread since propagation is predominantly Line-of-Sight (LoS). The reduced symbol duration and wider SCS open up the implementation of URLLC services, as the latency is reduced and there exist more frequent opportunities to schedule the transmissions.

Then, the concept of BandWidth Part (BWP) arises, consisting in the division of the available bandwidth into portions where different numerologies are used. This way, each BWP can be used to allocate users demanding different UCs, e.g., a URLLC user can be allocated in a BWP with a wide SCS (shorter symbol duration), while a eMBB user can be allocated in a BWP with a narrow SCS (longer symbol duration). A single UE can be allocated up to four BWPs simultaneously. Although only one can be active at a time, this allows the UEs to use multiple UCs.

### 2.2.2.1 Beamforming

The beamforming technology is a centric aspect of the current thesis, as it is one of the main novelties of the 5G NR. However, it can only be understood together with the concept of MIMO. The MIMO technology is considered a cornerstone of NR. Despite the fact that it was introduced in LTE Release 13 and 14, NR has boosted the benefits with a combination of MIMO and beamforming [44].

MIMO consists on the utilization of multiple antennas at the transmitter and receiver to improve the data rates and the signal quality. In comparison to the 3-sector frequency reuse from LTE, MIMO and beamforming allow delivering multiple data streams. Even though a beam per user is not feasible yet, it gets finer spatial granularity, which enables a more efficient reuse of the spectrum.

The signals are transmitted over the radio channel, and received after being affected by the propagation losses, reflection, refraction, scattering, multi-path effect and interferences. Similarly, there are effects such as shadowing, fading, destructive

interferences and noise, that jeopardize the communication.

The use of the MIMO technology is better understood progressively:

- **Single Input Multiple Output (SIMO):** It uses multiple antennas at the receiver, achieving a diversity gain by receiving two versions of the same signal that can be combined to improve the signal quality. The more uncorrelated versions of the signal, the better the diversity gain. When a version of the signal is affected by a deep fade, the other version may likely be good enough to recover the signal.
- **Multiple Input Single Output (MISO):** It uses multiple antennas at the transmitter and leverages the spatial diversity of transmitting the same signal from different antennas, as the channel will affect the versions disparately. The receiver can combine the signals to improve the signal quality, e.g., compensating for the destructive interference affecting one version by using the other, likely unaffected, version.
- **Multiple Input Multiple Output (MIMO):** It uses multiple antennas at both the transmitter and receiver. Here, it can benefit from the spatial multiplexing at both sides, but it can also achieve a multiplexing gain by transmitting different data (named streams or layers) from the different antennas, and therefore increasing the data rates. Again, when the channel is diverse enough, the signals will be received decorrelated, and the receiver can separate them to recover the data. The number of streams is limited to the number of antennas at the transmitter or receiver, concretely the side with fewer antennas. The receiver can provide feedback to the transmitter to improve the precoder weights and increment separation between the signals. This is known as Single-User (SU)-MIMO.
- **Multi-User (MU)-MIMO:** It bases on the same concepts as SU-MIMO, but each stream is intended to a different user.

All the aforementioned techniques exploits the same spatial and time radio resources to improve either the signal quality or the data rates. To achieve this, the antenna elements must be sufficiently separated, at least half a wavelength, to acquire adequately uncorrelated signals.

In addition, the number of antenna elements impacts the Effective Isotropic Radiated Power (EIRP), then the regulatory aspects come into play.

On the other hand, **beamforming** exploits the MIMO technology differently, i.e., to steer the signals to one or more specific directions, achieving a twofold benefit: it increases the capacity by reusing the spectrum for users that are spatially separated; and it improves the signal quality by focusing the energy, which make the transmission more robust to obstacles and channel effects, but also reduces the interference and the noise.

This is done by changing the phase and amplitude of the transmission to each element of the antenna panel to artificially create a constructive interference in the desired direction, and a destructive interference in the rest of directions. In contrast to MIMO, beamforming needs an antenna separation around half a wavelength, as larger spaces (suitable in MIMO) may lead to undesired lobes in other directions.

The higher number of antenna elements the narrower beams will be manageable to generate. This is also related with the use of beamforming at FR1 and FR2. As the frequency increases (FR2), the antenna elements can be closer each other, so the total antenna size can be reduced. Thus, the beams used at FR2 are usually narrower than the ones used at FR1. This is also beneficial as the beamforming gain increments, which is preferred for mmWave signals since they are more sensitive to the radio channel.

Beamforming can work in two modes: passive, where the beams are static, and the users switch between beams as they move; or active, where the users are tracked, and the beams are reconfigured to keep pointing to them. To the best of the author's knowledge, the active mode is not yet present in commercial deployments of 5G networks, so the different manufacturers implement a compilation of beams sets that can be configured in each cell.

The operation of beamforming relies on precoding matrices that modifies the phase of each signal. This process can usually be done either at the digital domain, where it needs computational resources, or at Random Forest (RF) domain, where analog phase shifters work easily. In the latter case, the change of beam directions is slower and more complex, so it is feasible for static beams configurations. Also, being  $K_{BF}$  the number of RF chains and  $M$  the number of antenna elements, there are three possible schemes: analog ( $K_{BF} = 1$ ), allowing only one direction at a given time; digital ( $K_{BF} = M$ ), enabling the transceiver to direct beams at many directions; or hybrid ( $K_{BF} < M$ ), where the transceiver can simultaneously use  $K_{BF}$  directions. The latter two means that the transmission power must be reduced

by the number of directions/beams, because the total power constraint in terms of EIRP applies to the beams on balance.

Regarding coverage, the use of beamforming has allowed the MNOs to use the same physical sites when upgrading to the higher frequency carriers in 5G. The coverage areas they designed when deploying previous generation sites around 2 GHz carriers can roughly cover the same areas at 3.5 GHz carriers thanks to beamforming.

From a management perspective, the beams compose an additional logical layer, which is added to the Primary Synchronization Signal (PSS) (1 of 3 possible values), Secondary Synchronization Signal (SSS) (1 of 168 possible values), and Physical Cell Identity (PCI) (1 of 1008 possible values) that are used to identify the cell. The maximum number of beam is standardized as 8 at FR1 and 64 at FR2, although the shape or the distribution of beams is not standardized, and it is left to the vendors to implement it.

Moreover, it is possible to combine the benefits of both MIMO and beamforming. Here, when having an antenna panel of 4 rows of 4 cross-polarized pairs, making 32 discrete antennas in total, there are flexible options. If beamforming is disabled, up to 32 streams can be transmitted using MIMO. In contrast, it can also be configured to transmit 4 beams of 8 antennas each, i.e., up to 8 streams per beam. Here, FR1 can benefit from less variable channels and use higher order MIMO, while FR2 prefers low order MIMO and elevated number of beams.

Each beam has a unique Synchronization Signal Block (SSB) and a unique Channel State Information Reference Signal (CSI-RS), which are transmitted by the gNB, so the UE can measure the channel quality and report it to the gNB to adjust the precoding weights. The CSI-RS symbols are transmitted using the physical channel in a way that they can be decoded independently by the UE for each channel. To compress the reporting, just an index of a pre-defined precoding matrices codebook is sent. Concretely, the following information is reported back from the UE to the gNB:

- Rank Indicator (RI): It indicates the number of streams/layers that can be used by the UE.
- Precoding Matrix Indicator (PMI): It indicates the index in the precoding matrix codebook that the UE has selected.
- Channel Quality Indicator (CQI): It indicates the modulation scheme and

channel coding to be used based on the UE measurement.

However, the beamforming feature has motivated the NR specification to be more oriented towards the use of **TDD**, where the same frequency is used for both DL and UL. This has two main advantages: the DL and UL resources can be dynamically allocated, collaborating to the flexibility and adaptability main objectives of 5G; and the channel reciprocity, which consists on assuming that the DL and UL channel are sufficiently similar to reduce the overhead of channel information. In the latter case, the Sounding Reference Signal (SRS) that the UE sends to the gNB includes the channel information and the gNB computes the precoding weights, and select the best beam if beamforming is enabled.

Finally, regarding the UCs introduced in Section 2.2, the MIMO technology is an enabler for both eMBB and URLLC, as it increments the spectral efficiency and also the reliability of the communication, but the beamforming technology is oriented to support eMBB, as it increments the capacity by steering the signals and enables the use of higher frequency bands.

## 2.3 Open RAN

The O-RAN is considered as the next step in the evolution of the cellular networks. It constitutes a new paradigm that aims to disaggregate the different components of the network [40], also with the aim of providing a more flexible and efficient network. The concept of O-RAN comprises the virtualization of RAN components, i.e., implementing the components in software, and the use of Commercial Off-The-Shelf (COTS) hardware, i.e., general purpose or standard product [45]. Moreover, the word “open” stands for open interfaces, meaning that any vendor can provide a component that is compliant with the O-RAN specifications, and it can be integrated into the network, where multiple vendors will coexist.

To accomplish this, the network, and specifically the RAN, is divided into three main parts: the Central Unit (CU), the Distributed Unit (DU), and the Radio Unit (RU) [46, 47]. Figure 2.6 depicts the legacy protocol split, where the Base Band Unit (BBU) is hardware-based component that encompasses all the processing except the RF conversion (Fig. 2.6(a)), and the O-RAN protocol split, where the BBU is divided into the CU and the DU (Fig. 2.6(b)), and PHY can also be part of the RU (Fig. 2.6(b)).

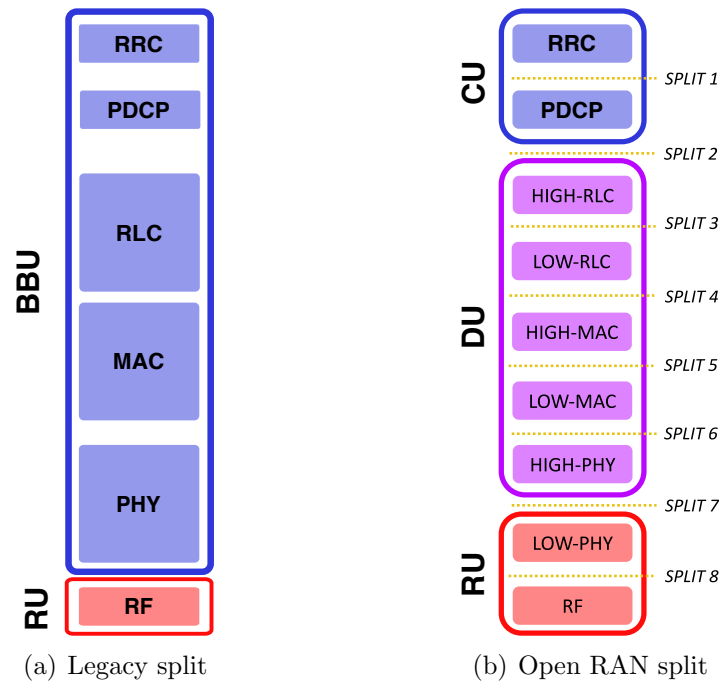


Figure 2.6: Evolution of functional splits towards Open RAN.

The split 7 (also known as split 7.2) has been supported by the 3GPP and the O-RAN alliance, a world-wide community of MNOs, vendors, and research & academic institutions with the mission to re-shape RANs to be more intelligent, open, virtualized and fully interoperable.

Therefore, the O-RAN architecture is based on split 7.2., and it is illustrated in Fig. 2.7. This architecture is characterized by considering the intelligence of the network as part of it.

On the one hand, the Radio Intelligent Controller (RIC) is a novel component that provides the radio with the capability to make decisions based on the network status. This is done through the development of third-party applications, concretely RAN Applications (rApps) and eXtended Applications (xApps), that can be deployed in the Non-Real Time (Non-RT) RIC or the Near-Real Time (Near-RT) RIC, respectively. The xApps run algorithms that can make changes to the network configuration in a period from 10 milliseconds and 1 second, while the rApps trigger changes that take longer than 1 second. Here, the interface E2 forwards the information and configuration commands between the Near-RT RIC and the CU-CU. Then, the interface A1 communicates the Near-RT RIC and the Non-RT RIC. On the other hand, the Service Management Orchestration (SMO) is a new element designed for rapid application development, and acts as a data



## 2.4 Network management

Network management is one of the keystones of cellular networks. They are designed to provide services to numerous users seamlessly in areas of hundreds of square kilometers. Then, the scope of mobile networks is formidable, and their management is a complex but essential task.

This management encompasses the network planning, configuration, optimization and problem resolution. They have been traditionally handled by human operators, and the MNOs as well as literature have devoted resources to the automation of these tasks through the definition of the SON concept [48], divided into three categories according to 3GPP [49]: self-configuration, consisting on the network being able to set its parameters according to the scenario; self-optimization, aiming at tuning network parameters to improve performance; and self-healing, which seeks to recover from faulty situations rapidly and without compromising the rest of the network.

In this sense, the following definition have been assumed according to [23]:

- Problem: A situation of service degradation, e.g., congestion.
- Fault cause: The reason that led to the problem, e.g., an incorrect parameter configuration.

The failure management process involves: detection (or prediction if possible), to identify the problematic situation; diagnosis, which determines the cause(s); compensation, comprising the actions to mitigate the problem; and recovery, to restore the service back to full operation.

This concept aims at reducing the Operational Expenditures (OPEXs) by minimizing the human intervention, but also at improving the network performance by making the network more responsive to each situation. Although, it has been evolved to ZSM [50, 51], which focuses on eliminating human intervention in all aspects of network management.

However, the complexity of cellular networks management has increased exponentially during each generation of cellular networks, as the number of subscribers has incremented, the services demand more exigent requirements, and the new features introduce new dimensions to be administered. In this sense, the novel services leverage in the concept of network slicing, where the requirements of

each service are met by a dedicated slice of the network, assuring a certain level of performance, e.g., latency, throughput, or reliability. Thus, the network management is a great candidate for AI/ML techniques to be applied, as they can handle the increasing complexity and generate insights in reduced time.

The Operations Support System (OSS) is defined as the main network element for management. It collects the data from the network elements, processes it, and provides the necessary information to make decisions. There are different kinds of data that can be used for network management. From the network side, the following information is utilized:

- Alarms: They are notifications that are triggered when certain conditions are met, e.g., high temperature in a component or cell load above a threshold.
- Counters: They are metrics that are continuously updated from the network elements, e.g., the number of UEs attached to a cell. They are also known as Performance Management parameters (PMs).
- Key Performance Indicators (KPIs): They are metrics that are calculated from the counters, e.g., the Handover (HO) success rate of a cell.
- Mobile traces: They are detailed logs of the message exchange between specific UE(s) and the network, e.g., the RRC connection establishment. They allow an in-depth analysis of the communication to diagnose problems, although they are usually disabled because they are resource-consuming, in both the user and network sides, and require a high storage capacity.

These data are vendor-specific metrics, so the definition of a counter or a KPI may be slightly different between manufacturers.

Additionally, there are metrics retrieved from the UE side. Here, the traditional way of collecting this data has been through the DTs, where a vehicle equipped with a measurement device drives through the area of interest, and collects the data. However, this is extremely expensive, time-consuming, and limited to the followed route, so the MNOs have been looking for alternatives, as the use of a renewed concept of crowdsourcing data collected from the UE that is detailed later on this thesis.

Lastly, there is a third source of information: the context. Context information has gained popularity in the last years, as many of the network problems are given

due to an external factor, e.g., a concert, a sport match in a stadium, big cluster in a square, or even the weather conditions.

### 2.4.1 AI/ML-based approaches

The Artificial Intelligence (AI) and Machine Learning (ML) techniques have demonstrated to be a powerful tool to address the complexity of the current network management tasks [52, 30].

The ML concept is a subset of AI that focuses on the development of algorithms that can learn from and make predictions or decisions based on data. These data contains features, which are the different inputs of the model. Then, ML is divided into three main categories:

- **Supervised learning:** The algorithms learn from labelled data, i.e., the data is previously tagged with the correct answer. Here, both classification and regression problems can be solved: the former aims to predict a category, while the latter aims to predict a continuous value with the minimum error.
- **Unsupervised learning:** The algorithms learn from unlabelled data. This means that the algorithms are intended to find patterns and relationships within the data. Here, there are also two main applications: clustering, which groups the data based on the similarities of the data samples; and dimensionality reduction, which removes the number of features of the data, i.e. to discard irrelevant information from the data.
- **Reinforcement learning:** The algorithms learn from an iterative process. There is a reward function that allows the model to explore combinations and take the decisions with higher reward in each case.

In the realm of network management, the ML techniques use all the aforementioned data sources as input features for the models. The traditional network problems can help the supervised learning models, while the new problems are still unknown for the MNOs, so the unsupervised learning models can be useful. The reinforcement learning, especially Deep Reinforcement Learning (Deep RL), is a promising technique to automate the network management tasks, as it can learn from the network status and take decisions to improve the network performance, monitoring the changes to restore the previous configuration in a

negative reward is observed.

## 2.4.2 Mobility management

The mobility management has been one of the most analyzed aspects of cellular networks. Given the mobile nature of the users, the network must be able to seamlessly Handover (HO) the users between cells.

Besides, the coexistence of RATs (e.g., 3G, LTE, 5G) implies that the users can switch between them, and the network is in charge of performing this Inter-RAT HO.

### 2.4.2.1 Handover

As mentioned before, the Handover (HO) process is a key aspect of cellular networks. The HOs are triggered based on different events, mainly based on: a HO hysteresis parameter, which defines how much better the signal quality (Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ)) of the neighboring cell must be with respect to the serving cell; and a Time-to-Trigger (TTT) parameter, that defines the time for the UE must remain meeting the hysteresis condition.

These HO-specific parameters are tuned in order to avoid unnecessary HOs as well as ping-pong HOs, which means that the UE is continuously switching to a cell and back to the previous one. Both occurrences are detrimental for the network performance.

However, there are other parameters affecting to HO, which are directly related with the coverage, as the cell power or the antenna tilt (the angle of the antenna with respect to the horizontal plane). While the users in the cell center are usually well covered, the users in the cell edge may suffer from coverage holes, ping-pong HOs, or low data rates. This has led to the undershooting and overshooting problems, where the cell coverage is too short or too large, respectively, in a specific scenario.

Moreover, 5G has introduced the concept of beamforming, described in Section 2.2.2, where an additional layer, in terms of reduced coverage added, is added to the mobility management.

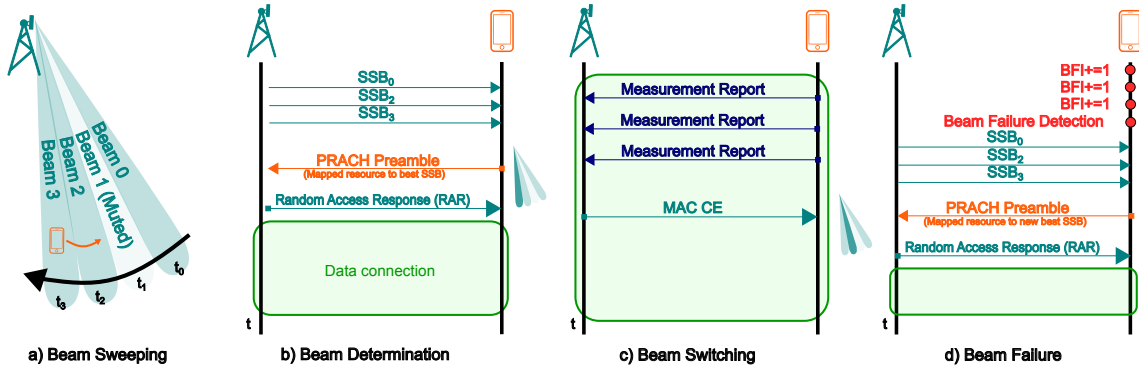


Figure 2.8: Illustration of beamforming procedures.

### 2.4.2.2 Beam Switching

This section introduces the most important aspects related to beam-based communications, which require for high-complexity procedures in order to establish and maintain the links [53, 54]. These procedures are divided into: beam determination, beam reporting, beam switching, beam failure detection and recovery.

Firstly, **beam determination** consists on the initial access performed by the UE using the Random Access Channel (RACH). It is based on the DL signals, known as SSBs, from the gNB, that are sent into different directions with a predefined periodicity (usually 20 ms), as depicted in Fig. 2.8a. The UE will send a Physical Random Access Channel (PRACH) preamble using the PRACH resource mapped to the SSB that received with the best signal quality during the **beam sweeping** period (see Fig. 2.8b). Beam determination was defined as a 3-steps procedure: P1, for wide beam selection (SSB-based); P2, for refined beam selection (Channel State Information (CSI)-Reference Signal (RS)-based); and P3, for UE side beam selection (also CSI-RS-based) [54].

Secondly, **beam reporting** consists on the periodical L1 RSRP beam measurements (up to 4 beams) that the UE reports back to the serving cell. In attached mode, these measurements are not based on SSBs but on CSI-RSs, that are sent in the Physical Downlink Shared Channel (PDSCH). The main advantage of CSI-RSs over SSBs for beam management is that CSI-RSs enables UE specific measurements. Nonetheless, SSBs are always transmitted since they are needed for initial attach, so they do not incur additional reference signal overhead in comparison to CSI-RSs. This is why 3GPP has added new definitions for UE measurements:

Synchronization Signal

(SS)-RSRP/RSRQ/Signal-to-Interference-plus-Noise Ratio (SINR), and CSI-RSRP/RSRQ/SINR. CSI-RSs are configured by L3 and mapped onto resources in frequency and time domain, for aperiodic, periodic or semi-persistent transmissions (first aperiodic cycle, then periodic).

Thirdly, **beam switching** is defined as the procedure where the serving cell can change the serving beam to another one based on the measurement reports received from the UE L1-RSRP measurements. It is considered as a procedure to enable intra-cell mobility, arisen from the introduction of beamforming. Here, the cell is in charge of triggering the beam switching, in the form of a MAC-Control Element (CE) [55, 56], as illustrated in Fig. 2.8c. This is a seamless operation, where the UE receives an indication to use a different beam in a Downlink Control Information (DCI) message, i.e., together with scheduling information. Unlike the **beam failure**, this is not detailed by 3GPP as a procedure. Also, as it occurred with handovers in previous generations, beam switching criteria is left to implementation. However, when this switching is not performed as expected, it may lead to a **beam failure**. Thus, the UE monitors the Radio Link Quality (RLQ) and sends a Beam Failure Indication (BFI) if conditions are fulfilled, e.g. RSRP measured on SSB or CSI-RS is lower than a threshold [57].

Lastly, **beam failure** will be detected after a configured number of consecutive BFIs (see Fig. 2.8d). At this point, **beam failure recovery** will be triggered, where the UE will listen to different beams on SSB or periodic CSI-RS and then proceed with Random Access (RA) to the best beam.

Moreover, L1-RSRP measurements are filtered (L3 filtering) to determine cell quality from the beam measurements so that it can be used for inter-cell mobility decisions.

Besides, beamforming configuration is flexible in terms of the number of beams that can be used in each cell, i.e., the beam set, so it can be configured with a low number of wide beams as well as a higher number of narrower beams, being also possible to distribute them vertically within one or more row, and a variable number of horizontally distributed beams. This may lead to undershoot and overshoot problems, i.e., beams that are covering too short or too long ranges, respectively, which may derive into ping-pong switchings or a high beam failure rate.

Here, beamforming-based intra-cell mobility introduces similar optimization problems than classic intra-cell mobility, meaning that beamforming configuration

becomes more complex, and even more scenario-specific: while the maximum number of beams in FR1 is 8, the specification supports up to 64 beams in FR2; in comparison with classic intra-cell mobility, where the intra-cell mobility was performed only between typically 3 wide ( $90^\circ$ - $120^\circ$  degree) sectors. The higher number of beams in the beam set the smaller are the coverage footprints they provide. Here, there is a trade-off between the number of beams and the periodicity of them being transmitted, both for SSBs and PDSCH.

Then, some beams could be blocked by any obstacle and therefore become useless for a given scenario. In this sense, it would be possible to use beam muting, i.e., disabling some beams from a beam set, as depicted in Fig. 2.8a. This option will reduce DL interference to near cells, as well as reduce DL signal strength to some directions, which is beneficial for energy saving purposes.

## Part II

# Development and Experimental Process

# Chapter 3

## Analysis and Identification of Potential Problems in 5G

### Content

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This section contains the work related to the first objective of the thesis. In particular, it consists of an initial analysis carried out on the current status of 5G technology, standardization aspects, and the main potential network problems that are identified.

### 3.1 5G Challenges

This work focuses on the Radio Access Network (RAN), known as New Radio (5G-NR). Given the mobile nature of users and the changing environment, wireless communications become more susceptible to failures, especially in 5G, where novel technologies are included.

The following general definition established by [23] has been assumed. A *problem* is a situation of service degradation, for instance, congestion. A problem is caused by the *fault cause* (failure), for example, bad parameter configuration.

There are novel features who have been introduced in 5G as enablers for better network performance, that may entail some disadvantages. Regarding mmWaves, they provide higher data rates, lower latencies as well as more capacity, since channels are larger at those bands. However, it is important to overcome their high path losses and their susceptibility to obstacles or outdoor to indoor propagation. For this purpose, beamforming techniques aim to minimize those effects by steering the signals onto predefined directions to improve the signal strength. However, beamforming schemes require the exchange of signaling between the gNBs and UEs in order to properly estimate the channel quality and maintain the link even when the users are moving. In this sense, TDD operation enables information transmission continuously in both directions using the same channel, so reciprocity can be assumed between DL and UL, and signaling overload is reduced. Although it may seem an ideal solution, the use of TDD causes interference between close gNBs if their patterns (i.e., time slots used for DL and UL) are not synchronized. Therefore, getting such higher capabilities is not always simple, and some drawbacks must be addressed.

For the sake of clarity, all identified problems within this thesis have been classified into three main categories: coverage, mobility, and interference. They are highly related to user positions and scenarios density and heterogeneity. On the one hand, Table 3.1 contains the most relevant identified problems related to 5G, together with a potential cause. On the other hand, Fig. 3.1 represents a complete 5G scenario, where key failures are depicted. The left part of the figure represents where different failures may occur within a complex scenario. The right part details the process of collecting information and metrics from the scenario and passing them to the OSS. The top right boxes relate the OSS functions with the 3GPP specifications. Moreover, the red boxes refer to LTE topics, green boxes to

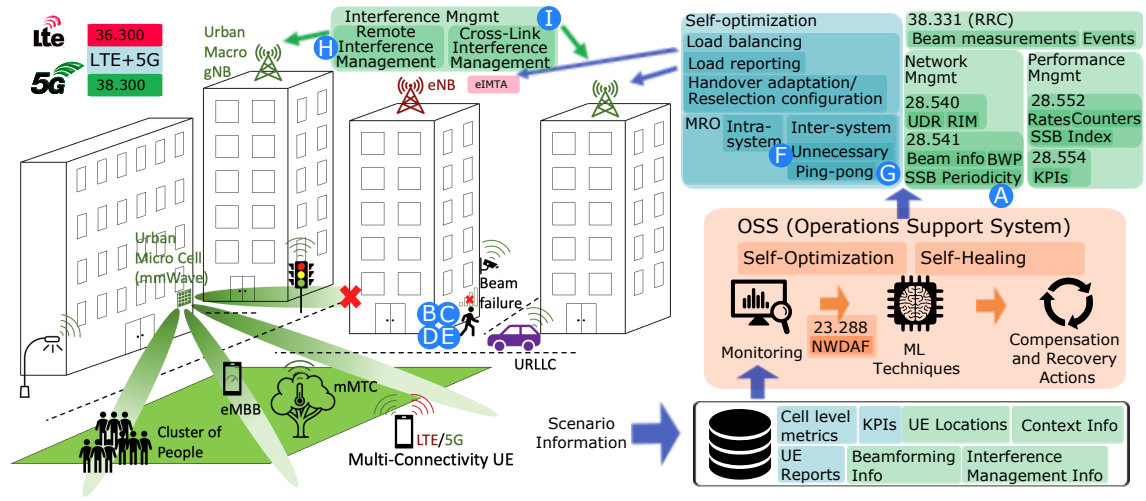


Figure 3.1: 5G heterogeneous scenario.

5G topics and blue boxes to LTE/5G common topics. 3GPP specification numbering is included for each topic. In addition, letters locate the problems described in Section 5G Challenges and Table 3.1 on the scenario.

In order to identify them in the figure, each of them are labeled with a different letter (A-G). Here, it is illustrated how an urban micro cell operating at mmWave frequency is being blocked by a building, so the beam becomes unsuitable at that location for the user. Here, beam switching procedures should be triggered when detecting the situation (See B, Fig. 3.1). In addition, two gNBs are providing coverage to close areas. Interference could likely occur as a result of the use of TDD, so it would be necessary to align their TDD patterns (See I, Fig. 3.1). These categorized failures will be extended in the following subsections.

Category	Problem	Potential Cause
Coverage	(A) Long time initial access	Beamset config.
	(B) Reduction in cell power	HW/Config. problem
	(C) Coverage hole	Beam blockage
Mobility	(D) Too late/early beam switching	Beam reporting config.
	(E) Too late/early beam failure detect.	L1 thresholds config.
	(F) Inter-system unnecessary HO	HO thresholds config.
	(G) Inter-system ping-pong	HO thresholds config.
Interference	(H) Remote interference	Out of sync TDD
	(I) Cross-link interference (CLI)	Out of sync TDD

Table 3.1: Identified Problems by Categories

## Coverage

Operators carefully plan each cell location to maximize the coverage with an optimal number of sites. Nevertheless, cells may fail or be improperly configured, so coverage problems will take place.

Here, the first identified failure is (A) *Long time Initial Access* (IA), and it is related to beamforming configuration. Thus, SSB are transmitted in a sweeping procedure, by changing beam direction for each SSB transmission with a periodicity ( $T_{SS}$ ). For very small  $T_{SS}$ , the impact of the SSB is considerable, with up to 43 percent of the resources allocated. In contrast, it enables a larger number of opportunities in which a UE can receive synchronization signals. This improves reactivity related to the tracking and the transmission of Channel State Information Reference Signals (CSI-RSs). If the number of directions to be swept is reduced, the beam sweeping procedure is completed in a single burst and  $T_{SS}$  does not impact the time required to perform initial access ( $T_{IA}$ ) [58].

Then, (B) *Reduction in cell power* is a problem that arised in previous generations. It usually depends on a hardware or wiring problem, but it could also occur due to a wrong parameter configuration. Regarding the latter, the beamforming configuration can be a possible cause in 5G. Failures can appear not only due to the larger number of antenna elements forming the antenna arrays, but also the beamforming scheme.

Similarly, (C) *Coverage holes* cannot be considered a novelty with respect to previous generation, but their probability of occurrence noticeably increases because of mmWaves propagation constraints. Their difficulty to surpass obstacles or their sensibility to external conditions will lead to this problem. Thus, it will be necessary to increase the capacity of coverage hole detection, even to detect beam-level coverage holes. The concept of occasional obstacle arises, so it cannot be assumed that holes are permanent on the scenario.

## Mobility

The mobility is an inherent characteristic of users in cellular networks, and it can lead to many problems as well. Although the occurrence of mobility problems in previous generations has been mainly caused by handover (HO) problems, the use of beamforming may lead to problems in concentrated areas such as beam failures,

which will need to be seamlessly fixed [56].

Although (D) beam switching is designed to be triggered automatically during operation, NR also supports UE triggered mechanisms to recover from beam failure. This occurs when the quality of beam pair link(s) of an associated control channel falls low enough (e.g., comparison with a threshold, time-out of an associated timer). (E) *Too early/late beam failure* can be considered particular cases of radio link failure (RLF). When a UE declares RLF being the cause a beam failure recovery problem, it is indicated to the network, therefore network notes it for future parameter optimization. Regarding too early beam failure determination, it leads to a latency increase, whose severity is determined by the use cases. In contrast, too late beam failure determination causes a connection outage, so recovery mechanisms take longer time.

(F) *Inter-System Unnecessary HO* arises with 5G-LTE networks coexistence. Handovers to LTE are performed, especially in cases of low link quality or lack of coverage. Triggering inter-system HO unnecessarily causes a decrease on system performance. Nevertheless, regarding Release 18, 3GPP System Aspects Working Groups (WGs) are promoting the concept of inter-Radio Access Technologies (RATs) HOs since inter-system and intra-system HOs only consider the core network changes and they are not as useful as RAT changes from a management perspective [59].

In a similar way, (G) *Inter-System Ping-pong HO* is also impactful, mainly in borders of coverage zones, where RATs recurrently change their availability (e.g., outside of a city). It is accounted when an UE is handed over back to the source cell within a predefined limited time.

## Interference

Interference has been an issue in every generation, but it has been traditionally addressed by acting on cells' transmission powers and tilt angles. However, two interference problems derive from the use of TDD, which is key for 5G networks operation as previously mentioned.

On the one hand, (H) *Remote Interference* (RI) refers to the case where distant cells interfere each other. This is typically caused by atmospheric phenomena which affects to signals by allowing them to reach distances farther than normal when they

are trapped in the atmospheric duct [60]. DL and UL transmissions are usually separated by a guard interval to avoid interference, but in case of long distances, propagation delay may exceed the guard interval, causing interference to cells which are sited far away.

On the other hand, (I) *Cross-Link Interference* (CLI) is a problem appearing between close sites. There are two types of CLI: gNB-gNB (or DL-to-UL), which means that an UE is transmitting data in UL to a gNB, but another gNB is transmitting data in DL, so its higher power may affect the UE transmission; and UE-UE (or UL-to-DL) interference, that happen when a UE is receiving DL data, but another close UE is transmitting in UL. They come out where TDD patterns are different from each other, and synchronization may not be the solution because of the different network services and requirements.

## 3.2 Applicable Standards

This section describes how the aforementioned network problems are considered and addressed in the network management approach defined by the 5G standards. 3GPP defines the standards for 5G. Nevertheless, there are some aspects missing which are particularly handled by networks operators (e.g., HO algorithms). Similarly, network failures are not usually described by 3GPP but the operators and literature spot them and work on their mitigation. Regarding 3GPP, specification numbering is used to divide subjects. Firstly, LTE subjects are contained in 36 series and NR aspects are introduced in 38 series, called *Radio technology beyond LTE*. Here, an overall description of each technology is provided in TS 36.300 [61] and TS 38.300 [60]. In Fig. 3.1, blue boxes refer to aspects that are shared between LTE and NR, while red and green boxes refer to specific aspects for LTE and NR, respectively. In the figure, numbers refers to specific 3GPP specifications where each issue is described. There are several differences between them as LTE is more evolved than NR, but the experience allows to become aware of some key aspects. An heterogeneous scenario is presented in the figure, including the three main UCs (eMBB, URLLC, mMTC) stated above. Then, information coming from the scenario is collected and used as input for OSS (Operations Support System) operation, where different actions could be taken for self-optimization and self-healing purposes.

In terms of mobility, it also introduces indications related to beamforming. The measurement model defined by a two-layer scheme for beam measurement: layer 1

filtering, where the UE measures a configurable number of beams to derive their quality; and layer 3 (RRC, *Radio Resource Control*) filtering, where cell quality is derived from multiple beams. But, Mobility Robustness Optimization (MRO), which is a 3GPP-defined feature, will need further development in order to efficiently support beam management, including beam reporting, beam switching, beam failure detection, and beam failure recovery procedures.

Regarding Radio Link Failure (RLF), UEs perform Radio Link Monitoring (RLM) based on reference signals and signal quality thresholds configured by the network. UEs are in charge of declaring RLF when meeting one of the multiple criteria (e.g., expiry of a timer started after indication of radio problems from the physical layer). *RLF cause determination* functionality is able to distinguish causes and report them, even informing about if they are related to an unsuccessful beam failure recovery.

Furthermore, it is key to retrieve information about the system performance. For this aim, 3GPP defines performance measurements, including performance indicators, which contain data aggregated over a group of NFs, or measurement families, which relate to a given functionality. This way, it is possible to obtain valuable data from the network perspective (e.g., radio resource utilization, number of RRC connections, counters about mobility management, etc). The latter includes the number of requested HO, distinguishing between successful and failed, as well as intra/inter-system, too early/late, unnecessary, and ping-pong HOs. In contrast, limited measurements are defined in terms of beamforming, except for the number of UE related to the SSB beam index, which can enable awareness about user physical distribution, which helps, e.g., to detect people clustering.

## Network Management Overview

The concept of SON (*Self-Organizing Networks*) was introduced by 3GPP in Release 8, and it encompasses Self-Configuration, Self-Optimization, and Self-Healing. Firstly, Self-Optimization aims to provide a high quality user experience while improving the system capacity, as well as to minimize human intervention to achieve it. Here, both specifications about LTE and 5G [61, 60] contain information about load balancing and MRO, where inter-RAT HO has changed its name to inter-system HO. However, application-layer solutions, which

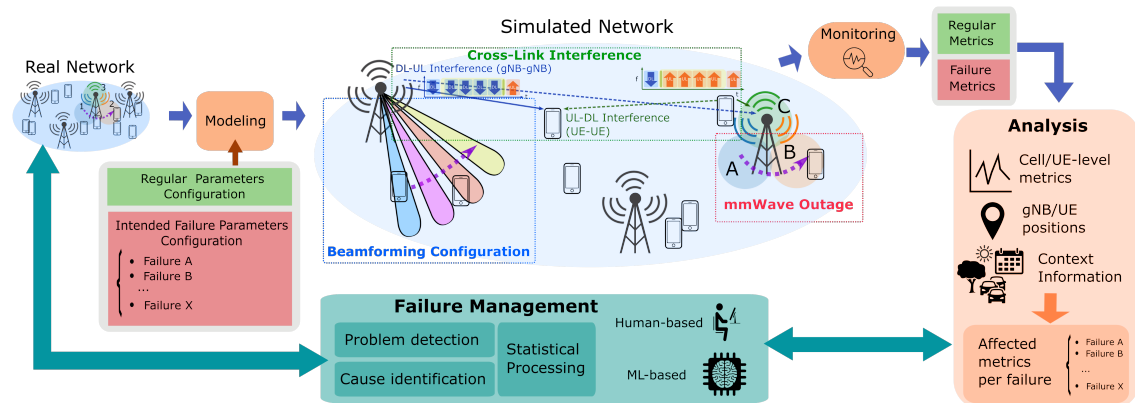


Figure 3.2: Failure Modeling approach.

means that high-level applications indicate their real-time requirements, are feasible for choosing the RAT from UE side, for example, not enabling the mmWave range if a chat application is not going to need it, but doing so when a video streaming application is running. Although they are not initially considered from network management, application-layer inputs are likely to be used as context information in a near future.

Interference, both remote and cross-link, are present in [60] and not in [61], which shows that they were not considered in LTE as TDD was only implemented in particular countries due to spectrum limitations.

Furthermore, the RRC protocol defines the events which are reported to the network: A2, serving cell becomes worse than threshold; A3, neighbor becomes offset better than special cell; A4, neighbor becomes better than threshold; and so on. These events are commonly used for HO algorithms configuration. Operators configure the thresholds and select the events to trigger (e.g., events A2 and A4 must be met). Although most events were defined for LTE, it is appreciable the *event I1* (Interference becomes higher than threshold), which is appearing for the first time in specifications.

5G establishes a Unified Data Repository (UDR), where Network Functions (NF) can store and retrieve data, becoming an important source of information for network management procedures. Classes and attributes are defined to have an overview about configuration possibilities (e.g., Bandwidth parts, SSB periodicity, per-beam information, etc). Beam-related information extends to beam azimuth, beam tilt, and vertical and horizontal beam widths. Besides, some key parameters and timers for optimization and healing purposes are: *qOffsetRangeList*, in charge

of specifying the metric (RSRP, RSRQ, or SINR) and the signal (SSB or CSI-RS) to be applied when evaluating candidates for cell reselection or triggering conditions for measurement reporting;  $threshXHighP/threshXLowP$ , a threshold used by UE when reselecting towards a higher/lower priority RAT or frequency band; or  $tReselectionNr$ , a cell reselection timer that can be multiplied with a factor if the UE is in high mobility state.

### 3.3 Simulation Results

The lack of 5G Standalone deployments is the major drawback for research. This leads to a difficult collection of information, including datasets, and promotes the use of simulators for this purpose. As for this study, ns-3 simulator tool [62] can be used to emulate some of the previous failure situations while retrieving metrics at physical layer. Regarding simulation tools, many of them are introducing propagation models that work at higher frequencies, as well as other changes at lower layers, for example, numerologies, since that they were previously defined in Release 15. But these simulation tools generally missing some of the key functionalities: HO, beamforming management aspects or system-level perspective.

Problem identification requires data monitoring. The gaps between UCs will complicate the problem identification due to the fact that a network configuration may be beneficial for some UCs while degrading the performance of others. Besides that, a failure can happen in a limited area, for example, one beam is being blocked by an obstacle. It is important to point out that this example will have more probability of occurrence owing to the less robust propagation characteristics in comparison with LTE. This limited blocking problem, which can be considered as a coverage hole, will affect only few users. Thus, the network will be often unable to detect them since general metrics (e.g., cell-level metrics) may not be affected. To detect this kind of failures, trace collection will need to be precise, which results in higher resource consumption. Similarly, if problems occur in a short period of time, they will also require to increase temporal granularity of network data collection. All this becomes even more complex with the number of variables to monitor.

In this respect, ML techniques will play a key role. They have traditionally been divided into three types: classification, clustering, and regression. Classification is referred to supervised mechanisms that requires labeled data to train the model, so it will be less applicable to these problems at first due to the lack of already classified

datasets. In contrast, clustering means unsupervised mechanisms where raw data can be used as input. This may be extremely important to differentiate the UCs, as mentioned before, really different among them. However, regression techniques will help us to predict how network will react in the presence of given characteristics, so the operators will be aware of the quality of experience they will be able to offer.

Here, the approach illustrated in Fig. 3.2 is proposed for the failure modeling of 5G networks. It consists of configuration sets, where the first is considered normal and the rest have intentionally misconfigured parameters. This is not affordable in commercial networks because it involves service degradations and outages, but in simulations or pilot networks it could provide insights on how the novel features may cause problems. The proposed framework aims to exploit metrics from network, users and context, being the latter not fully exploited thus far and whose acquisition is usually complex. This means that data from different sources will be different in terms of nature and format; therefore, they have to be integrated and unified. Then, the interpretation of the data could be done both via human experts, and statistical and ML-based algorithms, with the objective of detecting problems and identifying their causes. Thus, it is possible to compare all the reported information in both situations (normal and degraded) and check which metrics are affected the most in each case. In this sense, simulation offers the possibility to easily access them, for instance, the exact location of each user. Finally, this offline phase based on simulation will benefit failure management by extrapolating the algorithms to real network deployments, where some parts are immediate (e.g., data formatting and integration) and others (e.g., problem detection thresholds) may need adjustment to the real environment.

### 3.3.1 mmWave Outage

Firstly, Fig. 3.4 depicts the SINR degradation caused by a temporal cell outage under the scenario remarked in Fig. 3.3, where a single gNB is providing mmWave coverage to a single user.

It is important to highlight that three cells are sited in the same place with different azimuth angles, and the user is moving at constant speed following the path represented in violet color, i.e., a circular movement around the site. The path shows that the best cell quality according to user's position is given by cell A, but then the user moves to the coverage area of cell B. This is appreciable in the

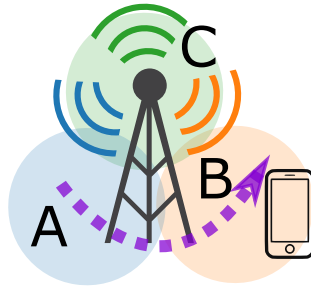


Figure 3.3: Scenario of mmWave outage simulation.

SINR graph, where the user starts reporting the orange cell as the best after the outage occurrence. Due to the fact that the simulation is working at 28 GHz carrier frequency, it is noticeable that the other cells SINR levels are mostly not suitable for the user. Similarly, marked peaks might be considered an obstacle, so the action to be taken should be different from the previous case as well as UC-dependent.

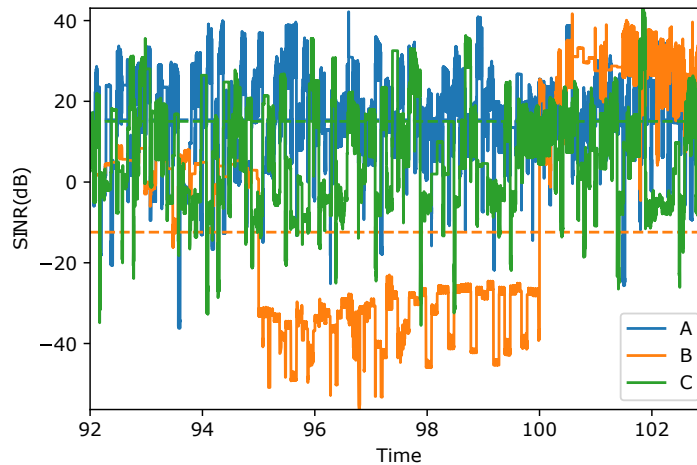


Figure 3.4: Perceived SINR by a user during an outage at mmWave carrier frequency.

### 3.3.2 Beamforming Configuration

On the other side, the periodicity with which UEs change the beam they are connected to is relevant, especially when they are moving perpendicularly to the beams directions, as shown in the dotted blue square of Fig. 3.2. The impact of changing the periodicity of computing the beamforming vector was simulated as it can be observed in Fig. 3.5. Thus, the left part of the figure represents the case where UE speed is 3 m/s while the right part corresponds to 10 m/s UE speed. In the figure, the SINR median, percentile, and extreme values are represented at

different gNB beamforming configurations, 8 and 16 beams, respectively. It is significant the relation between the UE speed, especially its angular velocity, and the SINR degradation experienced when the periodicity of beamforming selection was increased. The beamforming configuration with 16 beams is generally better, but it requires more antenna elements and signaling.

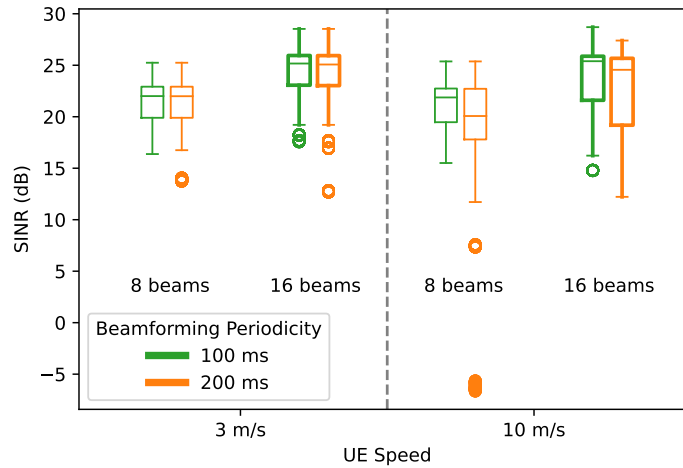


Figure 3.5: SINR degradation due to beamforming periodicity increase.

### 3.3.3 Cross-Link Interference

Finally, the CLI problem, depicted in the dotted green square of Fig. 3.2 is addressed. It is important to consider that TDD interference affects edge and center users differently. Global impact on mean SINR, computed from all users, is negligible, although it is considerable for certain users. This means that CLI will be difficult to detect from the network side since network metrics may not be affected. Fig. 3.7 represents the PDF of the SINR measured by the UEs located at the cell center and edge under two different TDD pattern configurations. In the figure, “low interference” (Low Intfc.) means that cells in the scenario are configured with different TDD patterns in order to minimize the interference (See Fig. 3.6(a)). Moreover, “high interference” (High Intfc.) corresponds to the case where all cells were configured with the same TDD pattern, so the interference would be maximum (See Fig. 3.6(b)). For the latter, it can be seen that interference leads to the appearance of up to three peaks on the SINR PDF, while the former pattern smooths those peaks, which means that SINR values are condensed in a smaller range.

Hence, in the context of 5G networks, there will be two aspects that will make

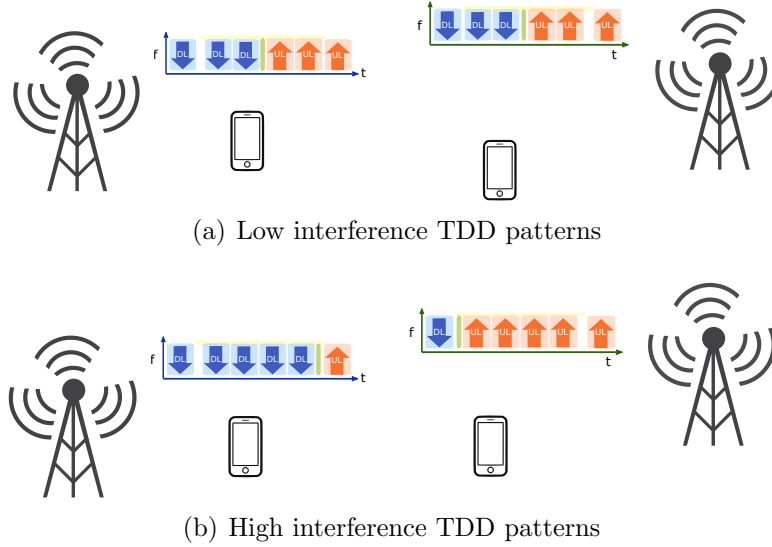


Figure 3.6: TDD pattern configurations for CLI scenarios.

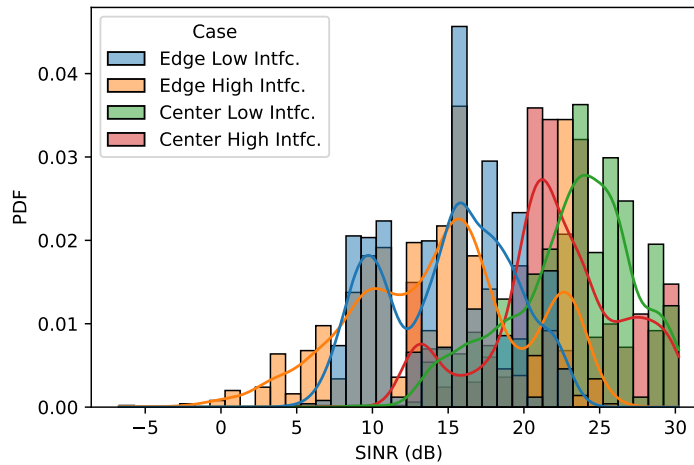


Figure 3.7: PDF of SINR degradation caused by Cross-Link Interference at both cell edge and center.

the difference regarding the preceding generation: the localization and the context. They will provide the network management algorithms a large amount of information collected from several sources, whether about events, weather or traffic [63]. This will open up new ways of processing such context information together with high accurate user locations. Thus, 3GPP System Aspects WGs, especially WG5 that is in charge of Management, Orchestration and Charging, discuss location topics in Release 18, such as the possibility of providing UE speed and orientation information to NWDAF through Minimization of Drive Test (MDT) data collection mechanism [59]. The modular 5G architecture is also in place for future integration of techniques that exploit these data.

# Chapter 4

## Beamforming-based Techniques Evaluation in Real Deployment

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This chapter is focused on the beamforming technology. Concretely, the content of this chapter encompasses two parts: the analysis of capabilities a real outdoor network deployment, where the network performance is evaluated by comparing both network and user side; and the study of beam switching at mmWave in an industrial indoor scenario, including refined criteria to enhance the beam switching.

## 4.1 5G SA Network at UMA

### 4.1.1 Architecture Description

In this section, architecture is described, including the details on the different elements. The infrastructure operates in 5G SA mode. Figure 4.1 depicts the main differences between 5G SA and NSA architectures, which resides in the need of the LTE RAN and Core (EPC). In the figure, the right part illustrates the components of the core networks, mapping the elements from EPC to the new components in the 5GC.

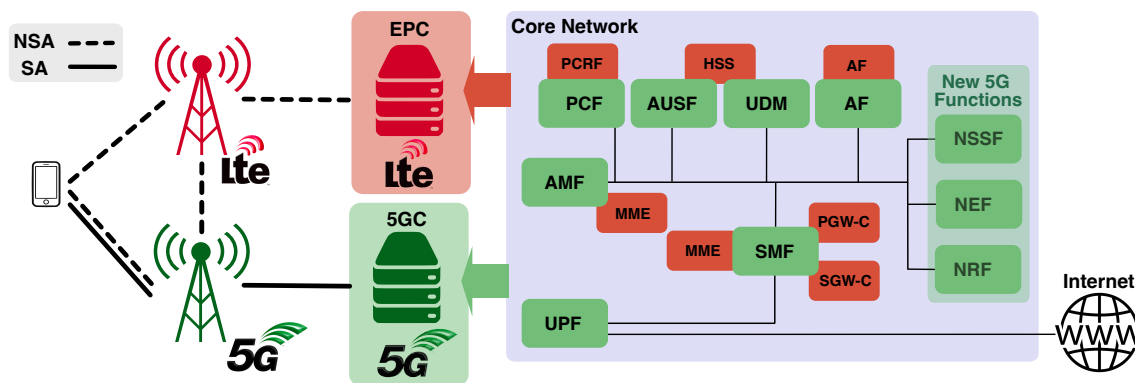


Figure 4.1: Cellular network architecture for 5G SA and NSA, including the mapping between elements of 5GC and EPC.

Figure 4.2 depicts the 5G SA network architecture, based on Nokia equipment that is deployed at UMA premises.

#### 4.1.1.1 RAN

Firstly, the RAN is divided into two parts, indoor and outdoor deployments. They both work at band n78, but at different sub-bands, and use TDD. On the one hand, indoor BTSs are divided into six pRRHs, acting as two logical cells. This means that pRRHs operating synchronously as a single cell will be transparent not only for the users but also for the network itself, since there are no individual counters or KPIs per pRRH and no handover are required from one pRRH to another. However, it is possible to turn them on or off individually for energy saving purposes or coverage measurements if required. They are configured with 50 MHz Bandwidth (BW) and maximum output power of 20 dBm. They are placed inside the Superior Technical School of Telecommunication Engineering

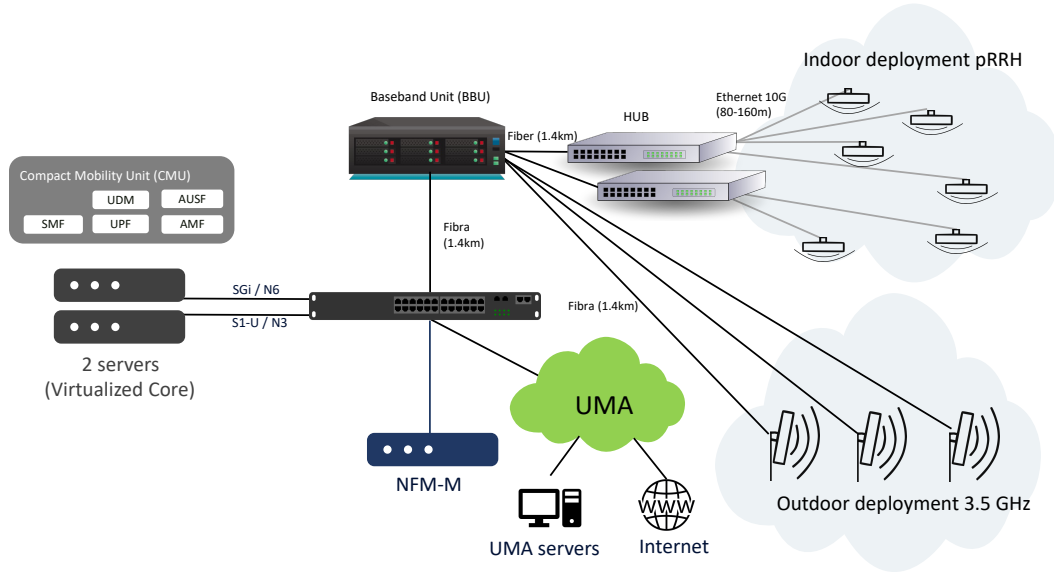


Figure 4.2: 5G SA Network Architecture deployed at UMA.

(ETSIT) building at UMA campus, covering two different floors and modules of the building.

On the other hand, three outdoor cells are deployed in the front part of the building, where there is a parking slot along with a smart natural park that belongs to UMA. They work as individual cells, and support beamforming up to 8 beams, where a set of different beam set configurations is available. Also, they are configured with 100 MHz BW and maximum output power of 31.9 dBm. The RAN parameters of the deployment are summarized in Table 4.1.

In addition, all radio parameters regarding RAN are configurable within the infrastructure's both indoor and outdoor deployments, including the most novel features, as TDD, where it is possible, e.g. to change the UL/DL patterns.

RAN Characteristics	Indoor	Outdoor
Number of Cells (pRRH)	2 (6)	3
Bandwidth	50 MHz	100 MHz
Band	n78	n78
Max. Output Power	20 dBm	23 dBm
Horizontal Coverage	Onmidirectional	$\pm 60^\circ$ (7 dB)
Beamforming	No	1, 2, 4, 6, 8 beams

Table 4.1: RAN Parameters of the 5G SA Network

Lastly, the physical scenario is illustrated in Fig. 4.3. Here, the colored areas illustrate the estimated horizontal coverage amplitude of the cells, although the

maximum range is not fairly represented. The remaining 3 pRRHs are placed on the 1<sup>st</sup> floor, specifically in the laboratories 1.1.1, 1.1.2, and 2.1.1, where the middle number corresponds to the floor and the last one to the room. Hence, they can be easily located as well when looking at the Fig. 4.3.

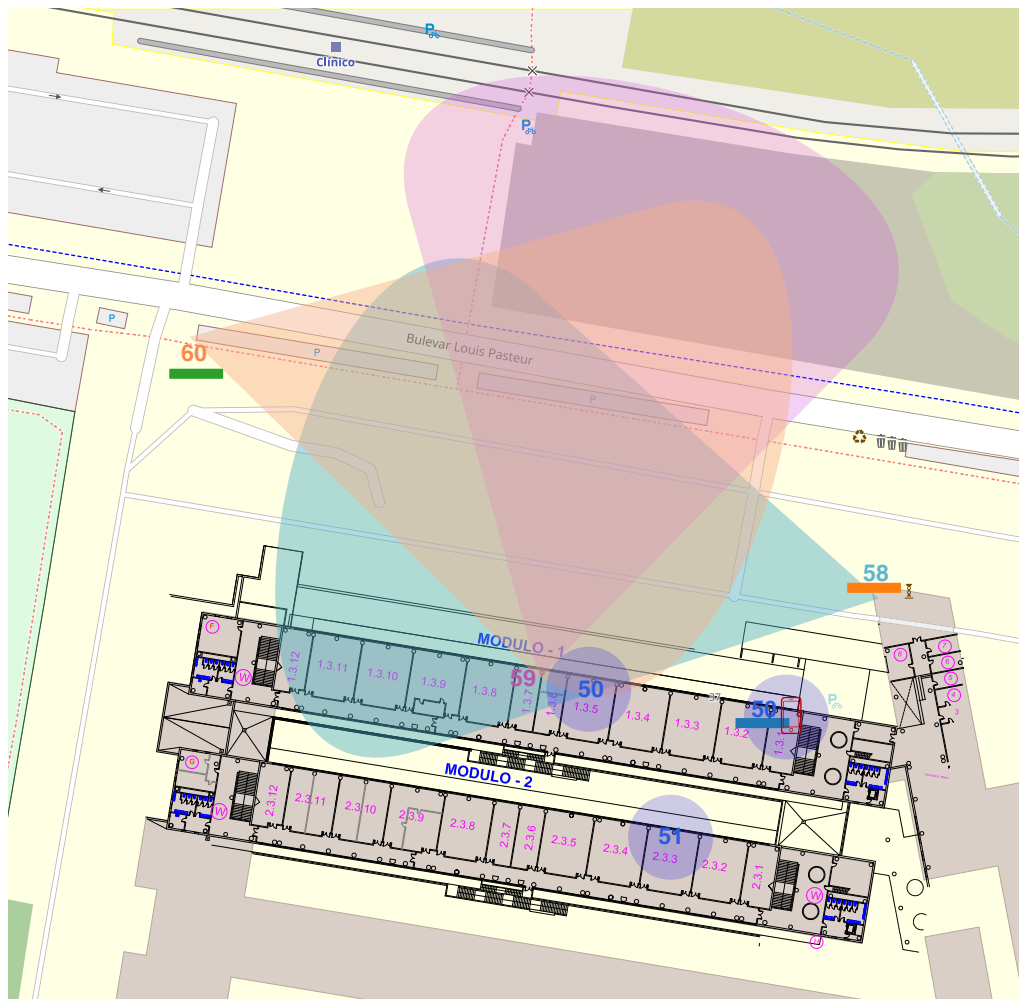


Figure 4.3: Physical scenario for the outdoor and 3<sup>rd</sup> floor indoor cells. Each number represents the Physical Cell Identity (PCI).

#### 4.1.1.2 Core

The network core is completely virtualized on 2 redundant servers that have two 25 Gigabit Ethernet (GbE) links between them, and two 25 and 10 GbE links, respectively, to main router. They work together for load balancing purposes as well as individually if there is an issue with one of them. They are running Nokia's proprietary Compact Mobility Unit (CMU), that includes the elements from 5G architecture: Session Management Function (SMF), UDM, UPF, Authentication

Server Function (AUSF), AMF. It is a fully commercial core with capability for hosting thousands of users, i.e. resources limitation would not be an issue regarding the core part. In addition, not being fully considered as part of the core, there is a component named Network Functions Manager - Mobile (NFM-M), that enables IP/MPLS management, including statistics and alarms related to traffic between network elements.

#### 4.1.1.3 User Equipment

Here, different alternatives to attach to the infrastructure are available. On the one hand, commercial phones attaching to 5G SA are currently restricted. However, it was possible to connect Samsung A52s as well as Motorola Edge 20 models to our infrastructure. On the other hand, external 5G modules that successfully connect are available as well: Simcom SIM8380G and Quectel RM510Q. In this case, they are usually connected to Small Form Factor (SFF) PCs or laptops in order to perform experiments on the network. Additionally, two Huawei Customer Premise Equipment (CPE) Pro 2 devices are in place to be used with XR equipment that do not have built-in 5G but Wi-Fi chipsets, like the Meta Quest 2.

#### 4.1.1.4 Self-hosted servers

Lastly, the infrastructure includes private servers which act as Mobile Edge Computing (MEC) servers for specific applications. Thus, a dedicated 10 GbE wired connection is available between the network core and servers. While Internet connection is usually shared between all users sited in the premises, there is sometimes a requirement to isolate the experiments in order to have controlled conditions. In the same way, Internet access is available to perform test with third-party services or for advanced phases of self-hosted experiments, where it is interesting to be tested under more realistic conditions, with traffic load and unknown server locations.

## 4.1.2 Key Capabilities

### 4.1.2.1 Network Configuration

The present infrastructure was envisioned as a powerful Research & Development (R&D) instrument since day one. Therefore, the attention was put on having complete control over all the network points. For the sake of conformity with Section 4.1, the same order is followed in this section.

Regarding the RAN part, cell configuration parameters are accesible. Any configuration could be set up without asking for permission to operators, since we have been granted to use a part of spectrum within the UMA campus area. Configuration plans can also be defined in order to easily activate them as desired. Here, access to all radio counters is available with a periodicity down to 5 minutes. This low value is not feasible for commercial operators given the higher number of cells they have deployed, but it is in our reduced scenario. Here, the historical counters are automatically collected and stored in a local database using a Structured Query Language (SQL) structure, and are available upon request. This is done thanks to a *Docker* container that has been developed in the scope of this work. Consequently, the data can either be visualized directly from the database using open-source tools, e.g. *Grafana*, or exported to a file for further analysis.

### 4.1.2.2 Metrics collection

Furthermore, these radio counters are usually the input for computing KPIs. Traditional and Nokia-defined KPIs are available, although there is even more interesting the capability of defining KPIs according to specific research interests, e.g. beamforming, since beam-based communication introduces multiple challenges and procedures in order to keep the connection up in a cellular heterogeneous scenario [64, 54]. The KPIs are not standardized metrics, so manufacturers define a large list of them with the aim of providing useful performance information to operators using their equipment. Although some KPIs have been used for many years by operators and literature, it has not been this way for novel 5G-enabled features. This capability has been utilized in this work (see Section 4.1.3) to perform an analysis on the beamforming-related information that is accessible from network side.

Regarding the core network, it is possible to access to core via CLI in order to

get real-time information about users currently registered and distinguish whether they are in active or idle state. Also, it is possible to register SIM cards in order to allow them to attach, and provide them with different traffic profile permissions, as well as define different Access Point Names (APNs) within the core. The message exchange tracing between core and RAN can be done, where it is possible to inspect messages, e.g. registration procedure. Here, the core statistics can be obtained directly from the CMU, but also through the NFM-M.

On the UE side, there are various alternatives to get the information. From lower layers, it is possible to collect Qualcomm logs and extract really detailed information directly from the modem to process it afterwards in an offline phase. This includes additional information coming from the modem as the localization information obtained from Global Positioning System (GPS). Nevertheless, application layer metrics can also be obtained from any application relying on Android Software Development Kit (SDK) to get cellular information, where it is possible to send it to a self-hosted server in real time for management purposes if desired.

Finally, service metrics, i.e. E2E, are available for different specific applications that rely on 5G for an adequate performance in terms of throughput, latency or other service-specific metrics, like CG [65, 66] or VR [67].

#### 4.1.2.3 E2E vision

Therefore, there is an added-value on the capability of relating all layer metrics in order to analyze how they jointly perform until different situations, services and configurations. This is called E2E perspective, and provides rich information of the whole system. This way, a service that is experiencing outages or bad performance at application level could reflect that behavior on the network counters or KPIs, so that it will enable network management towards the optimization for that specific service, while keeping in mind that there might be many services and users connected simultaneously to the same infrastructure, and it is usually not affordable to degrade them.

This section introduces results obtained on the described infrastructure in order to provide insights on the 5G SA network performance.

#### 4.1.2.4 Baseline Performance

At TCP/IP Layer, the network performance was measured by triggering simple experiments with the aim of obtaining throughput and latency values. Three experiments were performed in each case towards a private server directly connected to the 5G core: for throughput measurements, each experiment consisted in DL TCP traffic using iPerf3 tool [68] during 1 hour; for latency measurements, each experiment consisted in 1 million ping packets sent to the server with a wait time between sending each packet of 0.01 second.

Figure 4.4 plots the Empirical Cumulative Distribution Function (ECDF) of the DL throughput, as well as the complementary ECDF of the ping Round Trip Time (RTT) latency, both measured at UE side using the Simcom SIM8380G module. Only one cell was enabled during each experiment, so the UE was forced to be attached to the target cell, and a single UE was connected to the 5G network for the experiments. The target cells were: an indoor cell with a 50 MHz BW, and two outdoor cells with 100 MHz BW, sited in two different locations with respect to the UE position. Figure 4.4 reveals a better performance overall in terms of throughput for the indoor cell, despite the fact that it has a reduced BW with respect to outdoor cells. However, it is worth mentioning that the UE was stationary in an indoor location, less than 5 meters to the cell 50, and 30 meters and 125 meters from cells 58 and 60, respectively. These cells are underlined in Fig. 4.3 using colors from Fig. 4.4, and the UE is represented in red. Thus, the channel conditions must be much better in the first case. This would stimulate the idea of small cell deployments for indoor scenarios aiming at better performance, although it would require more work to delve into the real costs and expected benefits.

Furthermore, ping tests were performed under the same conditions. Latency results are also presented in Figure 4.4. The selected frequency of 100 ping packets per second was chosen in order to ensure that the UE stays in active mode, and does not go to idle mode at RRC layer. In this case, the indoor cell with reduced BW showed the highest latency results, while the outdoor cells showed lower latency values (See Fig. 4.4). However, minimum achieved latency is similar in the three cases.

In addition, a spatial overview of the throughput performance is depicted in Fig. 4.5. Here, only the cell 59 (See Fig. 4.3) is enabled, so it can be clearly noticeable the difference in terms of throughput between the center and the edge of the cell.

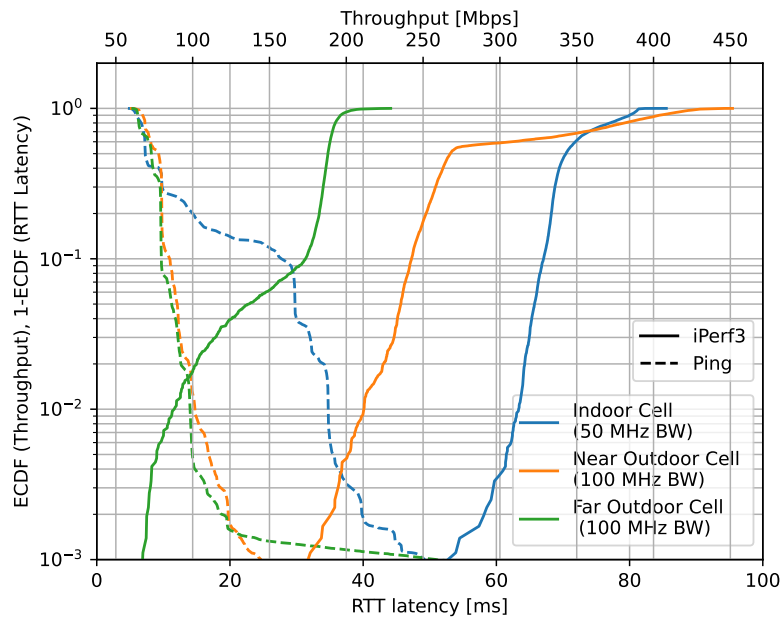


Figure 4.4: ECDF of throughput and latency measurements for UE connected to different cells. Note that CECDF is outlined in the case of latency.

The measured throughput is achieved using the iPerf3 tool [68] for DL traffic from a self-hosted server.

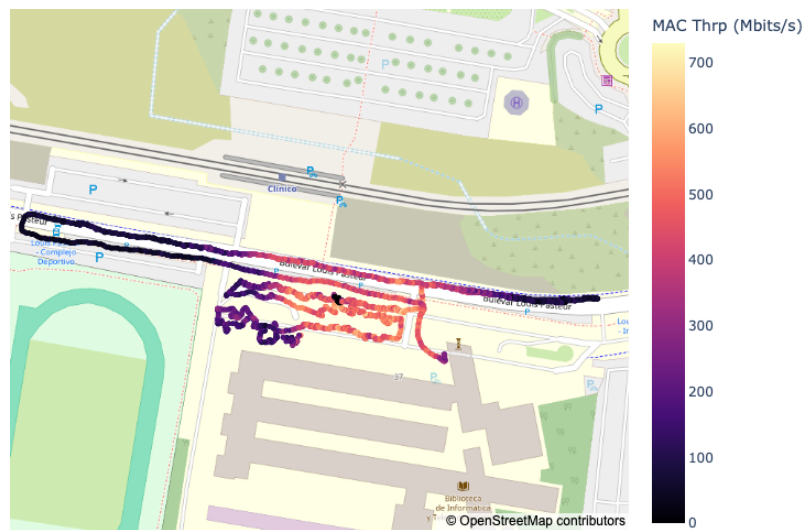


Figure 4.5: Map view of the throughput at MAC layer on the outdoor scenario.

#### 4.1.2.5 R&D Potential

The described infrastructure is envisioned as a powerful tool for R&D purposes. Here, the possibilities are open to different types of experiments, from radio configuration to application-layer performance. The configurability of the

infrastructure allows for testing cutting-edge network automation algorithms, as well as beamforming selection techniques, or mobility management strategies, either based on handover or beam switching. It is also affordable to evaluate energy efficiency techniques, like automatic cell sleep implementations, while measuring other KPIs and comparing the energy consumption of the cell during both normal and sleep modes. The cell power is a configurable parameter as well, so it is affordable to analyze network planning tools and algorithms, and compare the results theoretical results with the real field measurements. Although, the infrastructure is not compliant with O-RAN, some of the concepts that are envisioned to be implemented as rApps or xApps, may be preliminarily tested with non-automatic actions on the network. Moreover, as mentioned before, two complete service testing tools have been developed for the CG and XR UCs [65, 67], respectively. They are fully integrated to be automatically run under the desired network conditions, and configured to obtain service-specific metrics in real time. Finally, there are software tools from different vendors [69, 70], which are able to collect detailed radio and service quality metrics in order to verify, optimize and troubleshoot the network.

### 4.1.3 Beam-based Analysis

This section focuses on the beamforming feature introduced in 5G [64]. While the main motivation to use beamforming technology is to reach further distances and better signal quality overall, there are some drawbacks that need to be addressed, e.g. the beam switching [56, 71]. In addition, beamforming also enables some opportunities regarding localization or users' movement, that will be described in this section. The following experiments were conducted using the described infrastructure (See Section 4.1), and a Simcom SIM8380G module connected to a Lenovo L390 laptop running Ubuntu 22.04 acting as UE.

#### 4.1.3.1 Beam switching performance

The described infrastructure allows for location-based experiments within the UMA campus. A beam-based analysis was realized with the aim of analyzing the beam switching performance, and contrasting the serving beam IDs actually measured with the expected ones given the spatial distribution of the beam set as well as the UE location. Beamforming configuration can also be changed for a

better comparison. However, the reproducibility of the results gets complex due to the real field experiment factors, e.g., UE speed, exact physical route, and other uncontrolled radio conditions. Figure 4.6 illustrates the expected coverage footprints for each beam under an 8-beams configuration in the BTS, represented as colored sectors, together with the actual serving beam IDs at each position, represented as dots. While the expected results coincided with the actual results in the east area, the west area showed up an unexpected behavior: beam ID 7 was never reported. In this case, it was due to a firmware issue in the version that was installed in the cells, but it could also be related to a blocked beam due to a physical obstacle. In the presence of obstacles, the plot represented in Fig. 4.6 will not be that clear in terms of expected and serving beam IDs, and the beam switching performance will be affected.

A single UE was used for the experiments, and the location was registered with the integrated GPS of the radio module. Then, the statistics are computed from the raw data, and ping-pong occurrences, beam failures, and beam' Time of Stay (ToS), are analyzed, together with radio metric values before and after beam switchings. As described in Section 4.1.2, the infrastructure enables the network side data collection, which means that all the counters and KPIs are available for the joint analysis.

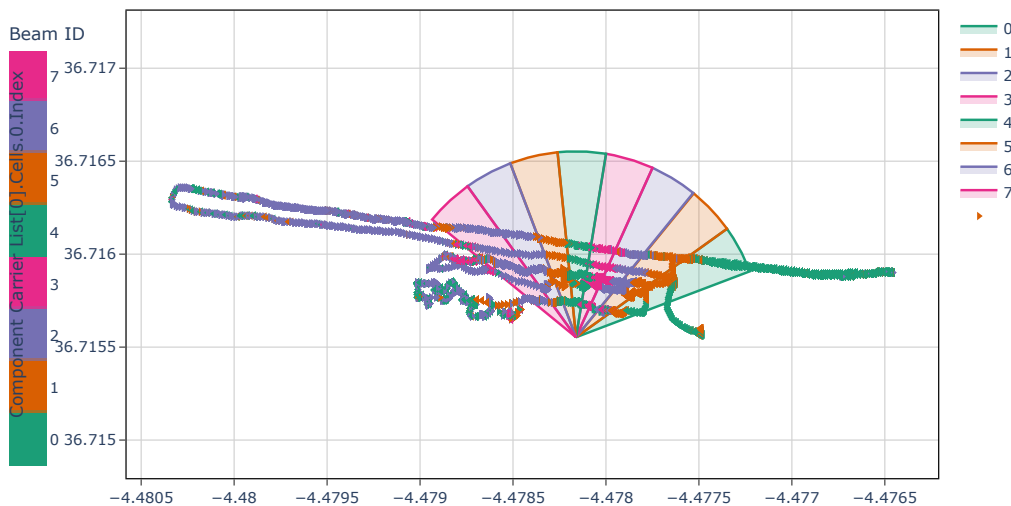


Figure 4.6: Beam set configuration of BTS (colored sectors) and UE's reported beam ID per location (color dots).

#### 4.1.3.2 Beam-based ML-powered localization

In 5G, localization is envisioned as key for network management tasks [28], as it provides useful information about attached users, i.e., common trajectories for

handover/beam switching optimization, crowded areas where the network may get overloaded, or the last user location before a coverage hole occurrence. Therefore, there are several works in the literature addressing the localization topic in 5G networks: using ML for Time-of-Arrival (ToA) estimation [72]; using unknown OFDM signals [73]; and based on multipath tracking for indoor positioning [74]. While there are efforts to standardize the localization information exchange between the network and the users, it is still not a reality in commercial deployments to the best of authors' knowledge. One of the main drawbacks is the privacy aspect, since knowing the user location at every moment is not well accepted by the users and regulation organisms.

In this respect, 5G networks introduce the beamforming features, as described above, in order to provide better coverage. However, the use of beamforming can be useful for localization purposes. The radio quality metrics has traditionally been utilized to determine how far the user is from the cell. With the information from two additional neighboring cells, the user location can be estimated using trilateration techniques. Here, the accuracy obtained is not enough, and it requires the visibility of three cells concurrently. Although, beamforming uses different beams horizontally distributed (vertical distribution is also possible) with different beam IDs. Given that the beam set distribution is known by the cell, the beam IDs provide the azimuth angle of the user with respect to the cell. In this case, the radio quality metrics determine the distance to the cell, so the user location can be estimated with a higher accuracy than traditional techniques. The proposed localization technique can be understood as a polar coordinate system, where the serving cell is used as reference point, and the distance and azimuth angle are retrieved from the radio metrics (RSRP, RSRQ) and beam ID, respectively. This is powered by ML techniques, and alternative algorithms may be used to outperform the obtained results in this work. Although this technique can not be compared to Global Navigation Satellite System (GNSS) accuracy, it is a good alternative to get localization from network side at no cost in terms of overload, since radio quality metrics and beam IDs are transmitted anyway.

For a proper comparison, localization estimation errors have been computed with respect to GPS location, which is considered the ground truth since it is outdoors, for different beam set configurations, and the results are shown in Fig. 4.8.

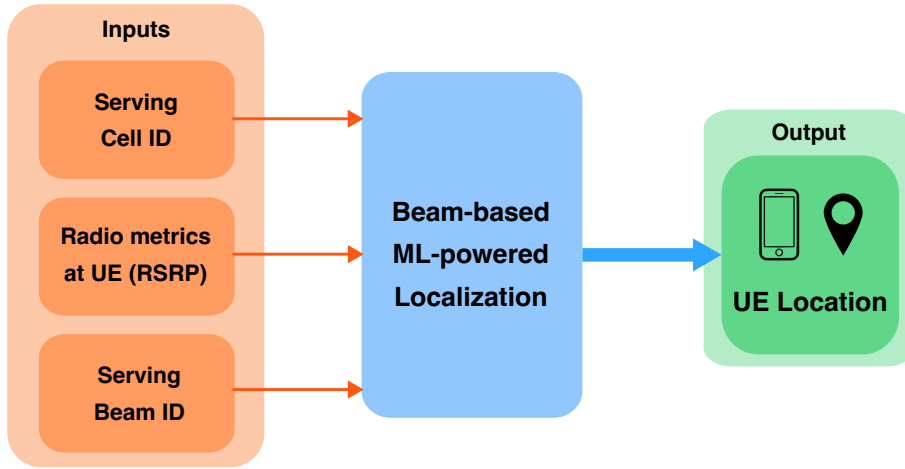


Figure 4.7: Scheme of the Beam-based ML-powered localization.

The estimation error represented in Fig. 4.8 is obtained by:

$$E = \sqrt{\phi^2 + \lambda^2}, \quad (4.1)$$

where  $\phi$  and  $\lambda$  represents the estimation error in latitude and longitude axes, respectively, with respect to GPS, both previously converted to meters before the ML-based estimation, and estimated individually.

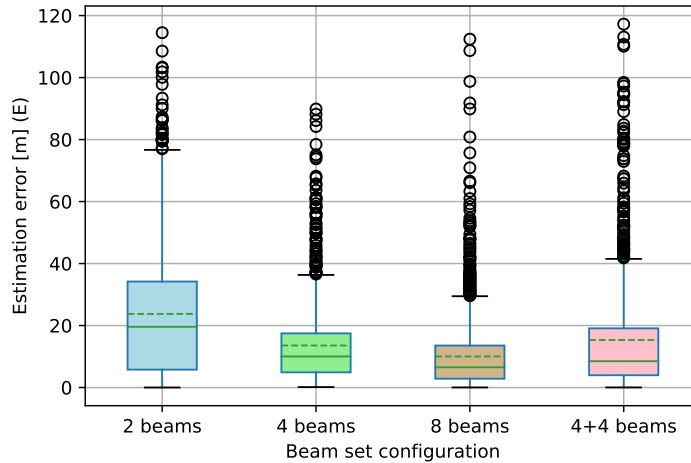


Figure 4.8: Boxplots of localization estimation errors for different beam set configurations. The boxplot shows the median, the first and third quartiles, and the whiskers represent the 1.5 interquartile range. Green dashed line represents the mean value. Outliers are represented with black dots.

Although it may seem that the localization estimation error is high, it is important to remark that the location information is obtained at zero overhead

cost, i.e. no additional signaling or measurements are required. Additionally, this technique can be extrapolated to indoor scenarios, where there are no better alternatives for localization other than Ultra-Wide Band (UWB)-based or other proprietary solutions requiring additional hardware deployment on site, to the best of authors' knowledge. Thus, the proposed technique provides location information to the user as long as a beamforming-enabled cellular network covers it, leveraging the control information exchanged for the cellular connection itself.

The scenario used in this work is 170m long and 50m wide, and the number of measurements was reduced. Based on the obtained results, a better model could be achieved using a larger scenario, and especially when considering the neighboring cell beams' measurements, which are also available on the UE side. In further scenarios, the distance to the cell could be estimated with higher accuracy since the difference in the received metrics (e.g., RSRP) is more significant, and the serving beam IDs are more distinct as the users are farther from the cell, i.e., fewer beam switchings will be triggered.

On the one hand, the knowledge of the localization information enables applications for the users, where the beam-based location can reduce applications' launching time, e.g., when it needs to search satellites. On the other hand, this information can be used on the network side for analytics to pave the way for new services for 5G verticals [26].

In addition, the proposed method becomes more interesting when considering mmWave deployments, where the attenuation is higher, the sensibility to obstacle increases, and the beam switching is more critical. Here, the localization information can be used to optimize the beam switching procedure, and reduce the number of ping-pong beam switchings [5]. Moreover, the maximum number of beams used at the BTS is 64 in 5G mmWave, which means that the azimuth angle resolution is higher, and the serving beam IDs gives more precise information about the angular range, then the localization estimation error could be reduced. Similarly, higher power attenuation provides higher accuracy in the distance estimation of the cell since the correlation between the radio metrics and the distance to the cell increases due to this fact. At mmWave, the use of beamforming is key for the operation, and the movement of the users may cause outages due to obstacle blocking, thus the localization plays a crucial role in the network management.

### 4.1.3.3 Novel KPIs Definition

The infrastructure allows defining new KPIs based on the available counters. The definition of KPIs has been key for traditional network management, since the combination of counters provided a richer overview of the network performance. Here, the advent of beamforming introduces new counters, related to serving/neighbor beams and beam switchings. They enable additional knowledge at network side that become useful from a network management perspective. In this work, multiple KPIs have been defined, and their values during the measurement campaigns have been analyzed.

First, a *UE Cross Movement (UEXM)* KPI is defined as the aggregated number of beam switchings considering the number occurrences from beams pointing to the left/west side from the gNB to beams pointing to the right/east side, and then comparing the sum with the opposite case, i.e. beam switchings from right to left. Then, the expression for *UEXM* is given by Eq. 4.2:

$$\text{UEXM} = \sum_{\substack{0 \leq x < N \\ 0 \leq y < N \\ x > y}} \text{BS}_{o_{x,y}} - \sum_{\substack{0 \leq x < N \\ 0 \leq y < N \\ x < y}} \text{BS}_{o_{x,y}}, \quad (4.2)$$

where  $\text{BS}_{o_{x,y}}$  is the number of beam switching occurrences from beam  $x$  to beam  $y$ , and  $N$  is the number of beams used in the beam set configuration.

Thus, this KPI provides information about *UEs' perpendicular movement with reference to gNB*. The network then knows how is the movement of the users, and it can be used for beam switching/handover optimization, since different patterns may appear in each cell regarding the hour of the day, the day of the week, or the season of the year.

Moreover, *Specific Beam Switching Ratio (SBSR)* is devised as a ratio that reveals whether a specific beam switching is occurring much more frequently than others. This KPI, unlike *UEXM*, would be categorized as a performance indicator. It is calculated as *the ratio between the sum of a specific beam switching, i.e. from beam  $x$  to beam  $y$ , with respect to the total number of beam switchings*. Although this KPI can be computed for each beam switching pair  $(x,y)$  individually, the most-repeated beam switching pair is considered the most relevant to extract insights about the current network performance. The expression for *SBSR* is

provided by Eq. 4.3:

$$SBSR = \frac{\max_{\substack{0 \leq x < N \\ 0 \leq y < N \\ x \neq y}}(BSO_{x,y})}{\sum_{\substack{0 \leq x < N \\ 0 \leq y < N \\ x \neq y}} BSO_{x,y}}, \quad (4.3)$$

where  $BSO_{x,y}$  is the number of beam switching occurrences from beam  $x$  to beam  $y$ , and  $N$  is the number of beams used in the beam set configuration.

*SBSR* close to 1 may imply undesired conditions (repeated beam switchings between specific beams). Even values lower, around 0.5, may be undesirable when the number of total beam switchings is high. This KPI must be taken into account in a weighted manner, depending on the total number of beam switchings, being more relevant as the number of total beam switchings takes higher values. If the total number of beam switching is 1, i.e. an extremely low value, *SBSR* must be ignored, since its value will also be 1, as it is the unique beam switching occurred.

Figure 4.9 sketches the evolution of the aforementioned KPIs for two consecutive days, where three of the measurements campaign were realized. They correspond to the results presented in Sections 4.1.3.2 and 4.1.3.1, so there was movement of users within the scenario. These defined KPIs are independent to the beam set configuration in use, they will be available as long as beamforming is enabled with at least 2 beams. The measurement campaigns consisted in continuous movement from one side to the other, and then back, for the sake of being served by all the beams within the beam set configuration. Therefore, the *UEXM* KPI represented in Fig. 4.9 is not high and neither maintained over time. This indicates that there is no tendency of users moving towards one particular direction. While the users are stationary, *UEXM* gets down to zero, as it is shown in the figure for the times between campaigns.

Besides, the *SBSR* KPI scarcely reaches 0.5 or more, which indicates that there are no switching that is being triggered much more frequently than others. This may happen, e.g. when a beam is blocked due to a physical obstacle, and the UEs are switched to the same another beam. A more in-depth analysis of the beam-related counters will allow detecting failures in the RAN network, e.g. ping-pong beam switchings, when the most-repeated *SBSR* and the second most-repeated *SBSR* are reporting significant values over a fair amount of time.

These counters enable new network capabilities based on the additional information they provide. Here, the information regarding the beam switchings

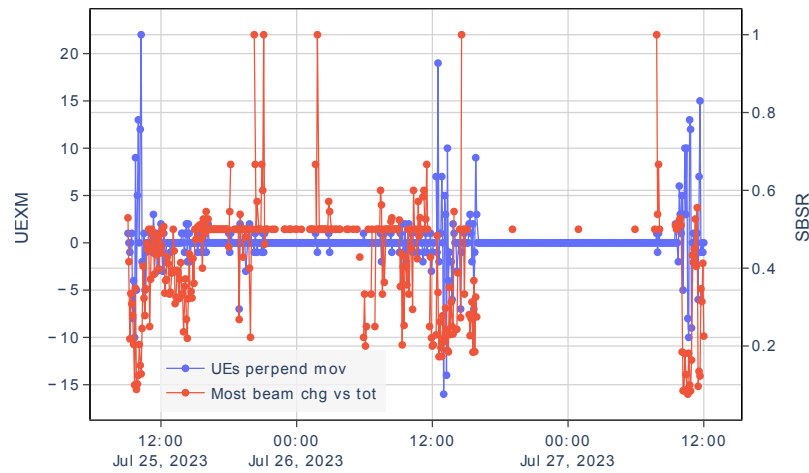


Figure 4.9: Evolution over time of defined KPIs for two consecutive days.

and serving beams over time may be used to detect clusters of static users, a high mobility area, or a beam that is never used. Therefore, the network management may predict problems as congestion, lack of capacity at a specific area, or potential coverage holes, in a more precise way than traditional KPIs.

## 4.2 5G mmWave Network at AAU

### 4.2.1 Equipment and Setup

This section describes the details of the setup used for measurements collection.

#### 4.2.1.1 Scenario

This subsection presents the indoor industrial scenario where the measurements have been collected. The scenario is part of the AAU 5G Smart Production Lab., located in Aalborg, Denmark, which consists in a realistic manufacturing and production environment with production lines, robotic arms and automatic pallet trucks [75].

The mmWave scenario covers an area of approximately 600 m<sup>2</sup> (hall 1 of the lab), where both Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) with the BTS conditions are given. Fig. 4.10 shows a panoramic view of the physical laboratory, illustrating the presence of high clutter.

In order to perform mobile measurements, we utilized an Autonomous Mobile Robot (AMR). AMRs are easily configurable to follow a predefined route, which was

set to be a two-minute loop that covers the main passable path of hall 1 (see Fig. 4.10), i.e., on the latitude axis (see Fig. 4.13). This route was designed to cover the maximum horizontal coverage width of the BTS. Although it was not possible to cover the vertical coverage width given the scenario, beam IDs from different rows are reported during the route, due to either angle variation between BTS and UE, or signal reflections. Here, as it is an indoor scenario, localization information is obtained each 100 ms from the AMR built-in Simultaneous Localization And Mapping (SLAM) system, which is based on Light Detection and Ranging (LiDAR), with cm-level accuracy.



Figure 4.10: Panoramic view of the AAU 5G Smart Production Lab.

#### 4.2.1.2 Network

A Nokia's AirScale, i.e., 5G BTS, is deployed inside the laboratory and belongs to a public MNO, so that any user connected to that MNO could attach to mmWave if they were in the laboratory and would own compatible equipment. However, no other users were connected to the mmWave BTS during the measurement campaigns. The BTS is composed by two Radio Remote Heads (RRHs) that point perpendicular to the route with  $\pm 25^\circ$  of azimuth, respectively, as shown in Fig. 4.3. Each RRH covers  $90^\circ$  horizontally so that there is an overlap of  $40^\circ$  between RRHs coverage areas. Regarding beamforming configuration, it uses a beam set providing 32 beams in total, including both RRHs, distributed in 3 vertical rows of 12, 12, and 8 horizontal beams per row, respectively, from top to bottom. It operates in the n258 band with six 100-GHz carriers.

#### 4.2.1.3 User Equipment

On the AMR, a Simcom module, SIM8380G-M2 mounted on an evaluation kit, and Qualcomm QTM545 mmWave antenna module were used. The module was

connected to a Lenovo Thinkpad L390 laptop running Ubuntu 23.04. The laptop had also a wired connection to the AMR to have fully synchronized information from both radio and position. The laptop ran the software Signaling Collection and Analysis Tool (SCAT) [76] to get information directly from the modem. At PHY, an update on the serving and the three stronger neighbor beams is received each 160 ms, including RSRP and RSRQ per beam ID. In contrast, MAC packets are received according to the data traffic that is currently being carried. In addition, a DL iPerf3 test is performed during the measurement collection with the twofold objective of keeping the mmWave link active and getting throughput performance metrics.

## 4.2.2 Experimental Evaluation

This section encompasses the analysis performed over the experimental measurements. The collected measurements are available in [15]. First, correlation is explored between the collected metrics, including radio, location and throughput. This initial assessment showed certain relationship between latitude (i.e., position in the y-axis), RSRP, and beam ID. In contrast, given the route followed by the AMR, it is expected the longitude (i.e., position in the x-axis) is not related because movement is done in the y-axis, except for any obstacle avoidance (see Fig. 4.13).

We retrieved the number of beam switching occurrences from the logs, using the reported serving beam ID. Here, we computed the statistics of beam switchings, beam's ToS, ping-pong occurrences and differences of radio metrics before and after the beam switchings take place. Figure 4.11 shows a graph of the reported RSRP over time. In the figure, it is noticeable the AMR loop-based movement, where two complete iterations are easily observable in the graph. The sequence of serving beams IDs, identified by different colors, within a loop iteration, is roughly repeated for all the iterations.

The beam set distribution is depicted in Fig. 4.12, from the BTS perspective, including the BeamIDs and the colors according to Fig. 4.11 and 4.13.

Figure 4.13 depicts the scenario, the beam ID reported at each point, as well as the theoretical coverage areas, represented by colored circular sectors, for the three vertical beam rows configured in the operating beam set.

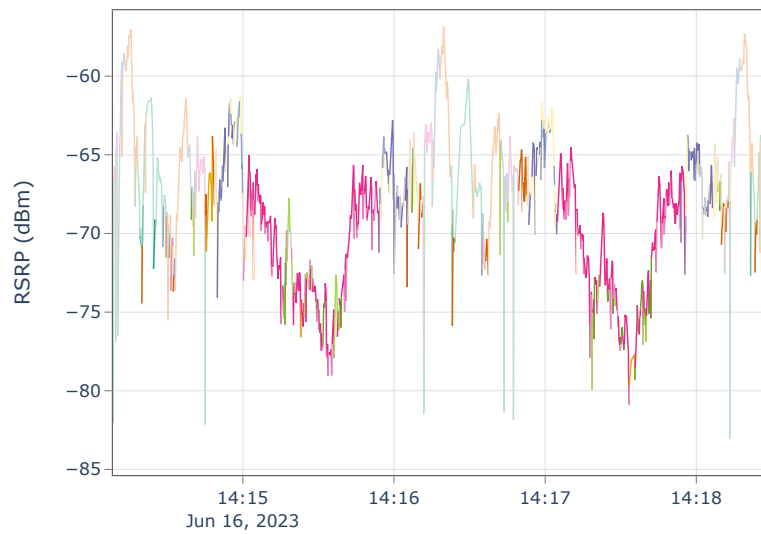


Figure 4.11: Time series of the RSRP. Colors are representing different beam IDs.

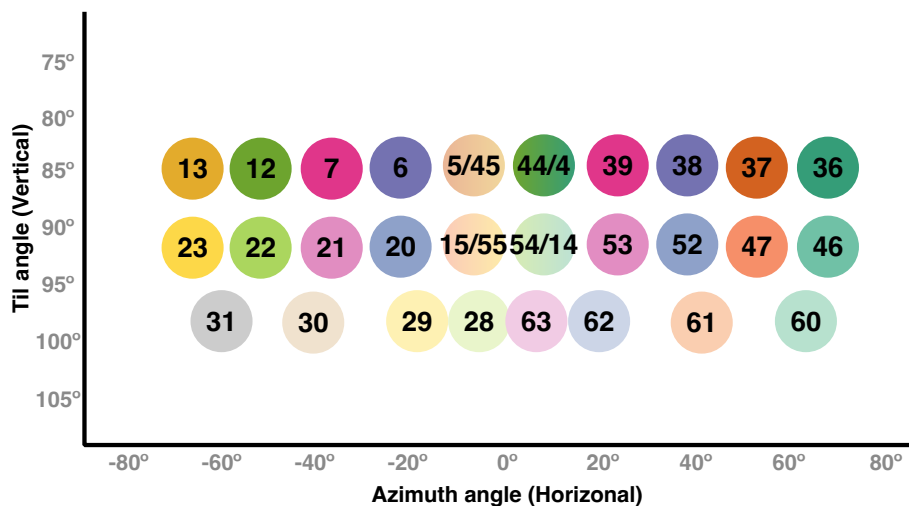


Figure 4.12: Beam set distribution with beam IDs seen from the BTS side.

### Main Observations

The following findings based on the measurements reveal aspects where beamforming operation could be improved:

Firstly, there are some beams that are never reported, as seen in Fig. 4.13 middle south zone of the top beams row or north zone of the bottom beams row. This means there is a subset of beams that are never used in the scenario.

In addition, there occurred a significant change in the scenario between measurement campaigns, consisting of the installation of a 3-meter-high industrial booth. This resulted in a change on the beams that were never reported. This

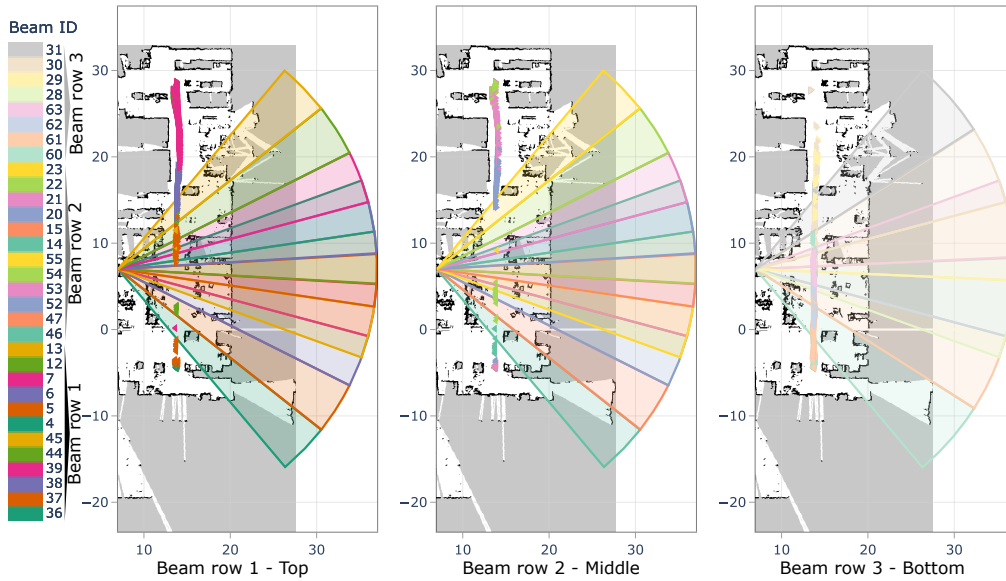


Figure 4.13: Scenario used for measurement collection with the beam set decomposition by rows of beams.

highlights the need for scenario-specific configurations in terms of beamforming, since there would be beam sets configurations that would be optimal in a given scenario while degrading the performance in others.

Then, it was observed that beam switchings are not triggered when the UE is stationary, even in such an indoor industrial scenario with high clutter. Thus, awareness about the movement of a user, i.e., using UE sensors (accelerometer, gyroscope), GPS, or indoor localization systems, could temporarily reduce beamforming-related signaling on CSI-RS while the user is stationary, which leaves more spectrum for data transmission. This makes even more sense for the Fixed Wireless Access (FWA) use case, where the UE is completely stationary. In this case, beam muting (described in Section 4) could play an important role for energy saving as well as interference mitigation with almost no consequences on the network operation.

Lastly, based on the observations made on the collected measurements, it was identified that RSRP reported by the serving beam was sometimes lower than the one reported by a neighbor beam. This means that serving beam was not always the best quality beam, so different beam switchings could have been triggered to achieve a better quality overall in terms of RSRP.

Here, the serving beam RSRP that was reported by the UE is considered as the baseline (**Measured RSRP**). The beam with the highest RSRP at each sample,

timestamp_time	beam_src	beam_dst	beam_tos	switch_v	switch_h	ping_pong	dist_src_to_ideal	dist_dst_to_ideal	rsrp_src	rsrp_dst
14:11:51.780	6.0	30.0	1.12	2	-2	0	(2, -1)	(0, 1)	-67.23	-67.88
14:11:53.380	30.0	12.0	1.6	-2	4	0	(0, 1)	(2, -3)	-64.36	-66.26
14:11:53.540	12.0	30.0	0.16	2	-4	1	(2, -3)	(0, 1)	-66.26	-64.34
14:11:55.140	30.0	31.0	1.6	0	1	4	(0, 1)	(0, 0)	-65.14	-68.15
14:11:55.460	31.0	30.0	0.32	0	-1	1	(0, 0)	(0, 1)	-67.82	-67.16
14:11:55.940	30.0	5.0	0.48	-2	1	0	(0, 0)	(2, -1)	-68.85	-69.59
14:11:56.260	5.0	30.0	0.32	2	-1	1	(2, -1)	(0, 0)	-68.16	-67.38
14:11:56.420	30.0	5.0	0.16	-2	1	1	(0, 0)	(2, -1)	-67.38	-66.9
14:11:56.740	5.0	30.0	0.32	2	-1	1	(2, -1)	(0, 0)	-66.97	-66.5
14:11:57.220	30.0	5.0	0.48	-2	1	1	(0, 0)	(2, -1)	-66.57	-67.38
14:11:57.540	5.0	30.0	0.32	2	-1	1	(2, -4)	(0, -3)	-66.61	-67.22
14:11:57.860	30.0	31.0	0.32	0	1	0	(0, -3)	(0, -4)	-67.37	-68.15

Table 4.2: Sample of beam switching data collected during the experiments.

either it is serving or neighbor, is considered as the upper limit of RSRP achievable the UE under the real conditions (**Best RSRP**).

### 4.2.3 Beam Switching Optimization

In this section, a set of conditions regarding beam switching is evaluated in order to get closer to the best performance case, i.e., the UE being served by the highest RSRP beam, as well as to reduce the number of beam switching occurrences, also considering ping-pong, i.e., where the UE is switched to a beam and consecutively switched back to the previous serving beam. As described above, being served by an inadequate beam could lead to service degradation or connection drops, due to the high sensitivity of mmWave links to the radio conditions. Here, the proposals are focused on the beam switching criteria optimization, i.e., the modification of beam switching decisions, which would determine a different serving ID sequence under the same conditions.

The beam switching optimization plays a key role in the industrial UC, where different actors (humans, robots, forklifts, etc.) will move around the scenario while attached to mmWave links. Here, the users' location and serving beam information could help to prevent them from being served by a beam that will suffer a degradation, e.g. by an obstacle limiting LoS given the user trajectory.

The following beam switching statistics from the raw logs were extracted: the beam's ToS before switching, the source and destination beam IDs per switching, and signal quality before and after the beam switching is completed.

This is represented in Table 4.2, where a sample of the time series for the beam switching occurrences is represented.

Consecutively, a set of conditions was defined, and the beam switching occurrences were labelled according to the conditions that were met in each case.

Firstly, the following conditions are based on radio metrics:

- **Short ToS:** The elapsed time since the UE was switched to a beam until it is switched to another beam is too short. Different values for this condition were checked, but showing similar performance, so that it was finally adjusted to 160 ms, i.e., minimum time between collected radio samples.
- **Ping-pong switching:** The user is switched back to a beam that was using recently. An integer value (named ping-pong level) was defined as 0 if there is no ping-pong occurrence, and greater than 0 to indicate how many beams have been serving since last time the destination beam was serving. Only positive values are possible for this metric. Lowest non-zero values are considered undesirable, since they mean unnecessary switchings are occurring. Similarly to the previous condition, we checked different values to meet this condition, but finally opted for value 1, i.e., UE is switched back to the last serving beam. Fig. 4.15 shows the histogram of ping-pong switching levels and the total number of beam switchings.
- **Switching distance:** It considers the beam set that the BTS is using, so that it counts for how many beams are there spatially between the source and destination beams. Switching distance will be 1 if the UE is switched from a beam to its contiguous beam, and greater than 1 if the destination beam is further within the beam set, i.e., an undesirable switching in principle. This is because users move slowly in comparison to measurement report frequency, so beam switchings should be triggered to contiguous beams under normal conditions. This distance is computed both vertically and horizontally. We defined the distance as greater to 1 to meet this condition, i.e., to account for switchings to not contiguous beams.
- **Lower RSRP/RSRQ:** Radio quality metrics after the beam switching have decreased.

Then, the localization information is obtained directly from the AMR, as described in Section 4.2.1.1, and merged with logs from the modem, enabling its use for the joint analysis. However, location is enriched by computing the Angle of Arrival (AoA), both vertical and horizontal, and relative distances between BTS and UE at each sample. Also, the theoretical coverage ranges for each beam in space can be

obtained from RRHs physical azimuths, i.e., the ideal beam at each UE location. Hence, the conditions below are defined with respect to localization:

- **Switching distance-UE direction mismatch:** This happens when the UE is switched to a beam which is pointing to a direction that is opposite to UE's current direction of movement. This is theoretically undesired, but it could happen due to signal propagation effects on the scenario.
- **Far from ideal beam:** It means the serving beam for the UE is not the one that is covering the current UE position and neither its immediate neighbor horizontally in the BTS beam set. We defined this condition for distances greater than 2 between serving and ideal beams, respectively, within the beam set.
- **To less ideal beam:** The beam switching is performed to a beam further than the serving beam given the beam set configuration.

Once the conditions are defined, they are combined in order to evaluate which of them could be used to improve the beam switching criteria currently in use by the BTS, i.e., **measured case** in Fig. 4.14 and 4.15. Thus, the **improved case** corresponds to the obtained performance when a subset of these conditions is considered for the beam switching criteria. Lastly, the **best case** is the upper limit of RSRP that could be achieved based on the UE measurements, i.e., considering the best quality beams on the UE regardless the BTS decisions of beam switchings. However, this is not affordable since it is the BTS who triggers the UEs' beam switchings.

Given the fact that real measurements taken in a realistic industrial scenario [75] are utilized, it is impossible to assume radio information that the UE did not actually measure. Therefore, it is important to remark that there is a condition that must always be met within this approach: when a beam switching is performed, the proposed criteria optimization could only consist on either switching to other beam between the reported ones or avoiding the switching to be triggered (as long as the serving beam is still reported as a neighbor beam after the measured beam switching).

Fig. 4.14 represents the ECDF of RSRP for the three cases: measured, improved, and best. The **improved case**, i.e., applying the proposed criteria based on radio

and positioning information, outperforms the **measured case**, especially on the lowers RSRP values, increasing 1.89 dB the minimum value, so that it could prevent connection drops due to peaks of low RSRP. In the figure, the **improved case** has been achieved by combining “lower RSRP”, “far from ideal” and “to less ideal beam” conditions, which have been proved to be the most relevant. It is important to remark that enabling these conditions would affect the decision to trigger a beam switching. Although, the reported radio quality may coincide with the measured performance if the proposed criteria decide as the current criteria does. At good radio quality conditions, performance differences are not appreciated.

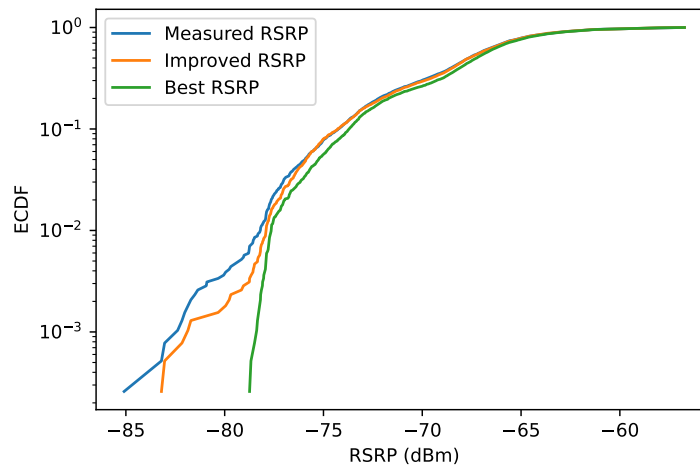


Figure 4.14: ECDF for measured, improved and maximum RSRP based on the measurements.

Lastly, Fig. 4.15 illustrates the ping-pong levels of the beam switchings in the left part, and the total number of beam switchings in the right part. Here, the ping-pong levels are compared for the three cases, demonstrating that **improved case** not only outperforms in terms of RSRP but also reduce the number of total beam switchings, in a 26.1% in total, with a 17.6% less of level 1 ping pong occurrences.

Thus, the proposed criteria optimization has demonstrated significant enhancement on the beam switching procedure, both in terms of radio quality and number of beam switchings.

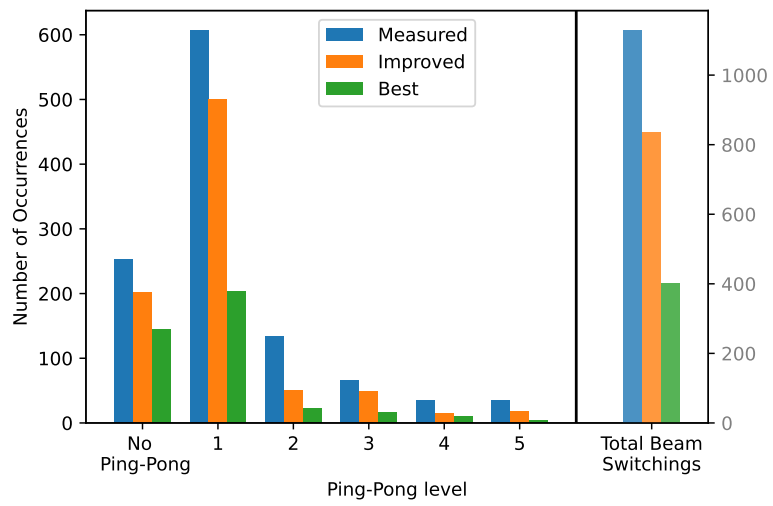


Figure 4.15: Ping-pong levels and number of beam switching.



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# Chapter 5

## Framework for the Integration of User-side Metrics and Localization Information for Network Management

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This section presents the development of a framework that integrates the proposed techniques. These techniques comprise the exploitation of user-side metrics and localization information for network management. This framework is tested with data from real commercial users as well as privately in real controlled environments.

## 5.1 Location-aware Smart Network Management

The system proposed in this section implements a set of capabilities that involve real-time processing of network measurements and events, the identification of users' locations, and the exploitation of location information to deliver smart network coverage prediction and failure detection. The PoC demonstrates the successful implementation of a set of containerized network functions (CNFs) that deliver location-based network management capabilities, and the integration with the developed LOCUS Platform capabilities, as shown in Figure 5.1.

This section will describe: 1) UMA Testbed, used to deploy a variety of wireless network technologies used for estimating user positions and monitoring network events; 2) LOCUS Platform and the common services that enable the development of smart network management functions, such as coverage optimization and failure detection.

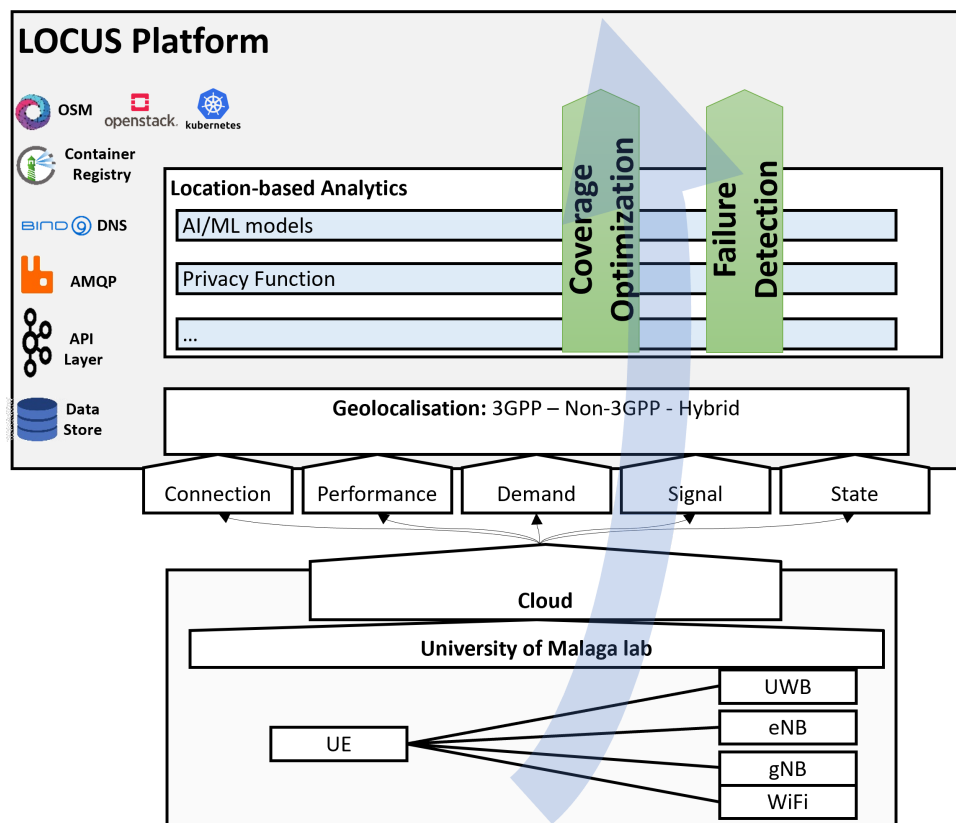


Figure 5.1: PoC Architecture including physical and cloud-based elements, and software solutions in use.

### 5.1.1 UMA Testbed

The physical scenario is composed by teaching laboratories placed in the Faculty of Telecommunication Engineering of the UMA, Málaga, Spain. It is an indoor scenario for R&D which is covered with a large amount of different technologies, including LTE, Wi-Fi, UWB and 5G. These are private deployments composed by real commercial equipment from different vendors. The scenario is depicted in Fig. 5.2. The cellular networks are independent and composed by three 5G indoor cells and five LTE picocells, respectively. Both private networks cells are co-located on the ceiling to cover the whole scenario with good coverage. The 5G cells work in SA mode and transmit with a SS PBCH power of -17 dBm and are centered at 3774.990 MHz, using TDD mode. The LTE cell parameters are configured with a transmission power of -6.8 dBm, DL frequency at 2630MHz, and UL frequency at 2510 MHz. The UWB deployment is based on Qorvo DWM1000 devices while the Wi-Fi Fine Timing Measurement (FTM) APs are Google Wi-Fi mesh routers and they were placed on top of shelves (2 meters height) in order to cover the whole scenario with good visibility. Both UWB devices and Google Wi-Fi routers are set to their default configuration parameters, considering only the 5 GHz channel for Wi-Fi operation. The UWB devices transmit with a power of -14.3 dBm and they are centered in 6 GHz. The scenario is a teaching laboratory which presents several metallic elements such as computers, shelves, etc. Therefore, it is expected that the measurements are heavily affected by multipath.

An Android application has been developed to capture all the ranging data from the network reference points: 5G and LTE base stations, UWB and Wi-Fi APs. The distance ranges with the 5G and LTE stations are estimated using the measured RSSI which is modeled by the indoor office propagation model [77]. To the best of our knowledge, there is no implementation yet to obtain more precise ranges in the cellular network, although localization based on Positioning Reference Signals (PRSs) are envisioned by 3GPP [78]. The WiFi-FTM ranges are directly obtained through the Android Application Programming interface (API). For the UWB measurements, each UWB device is attached to an UE and connected via Bluetooth Low Energy (BLE) to read the UWB data. A limitation on the performance of the UWB devices is that the UWB tag can only receive the information from four anchors simultaneously due to the software provided with the DWM1000 family products. Thus, in order to reduce the impact of the

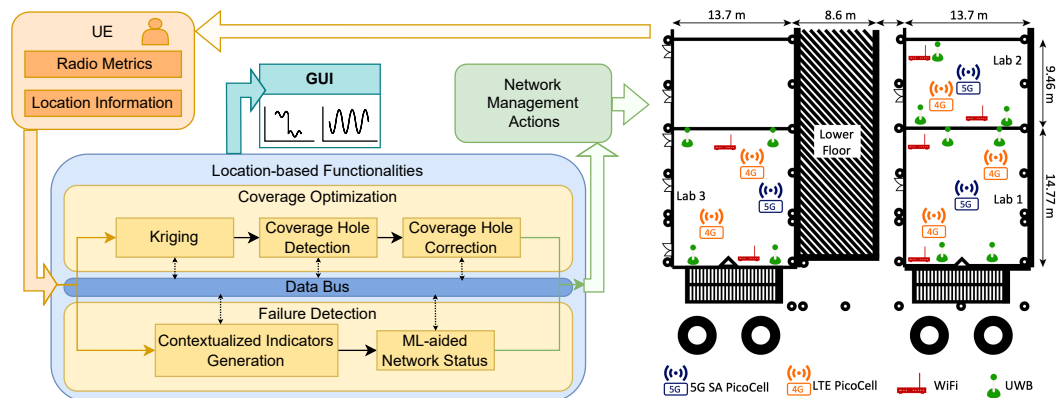


Figure 5.2: Functionalities components diagram together with the physical scenario sited at UMA premises.

reflections, the ranging information according to the Round-Trip Time (RTT) protocol is obtained. Timing ranging reduces the impact of multipathing in ranging estimations and the RTT neglects the need for clock synchronization as proposed for indoors technologies by [79].

### 5.1.2 LOCUS Platform

A unified and generalized platform has been designed and developed for the deployment of localization analytics functions and services, and their exposure towards Smart Network Management and 3rd party vertical applications that require (geo)location-awareness and analytics for their purposes [80]. More specifically, the platform in Fig. 5.1, named LOCUS Platform, implements localization analytics as a service solution on top of a flexible, scalable and virtualized infrastructure that allows to deploy and execute analytics services and functions (including ML pipelines) as virtualized elements across edge and core compute locations of the 5G network. This platform is physically sited in Athens, Greece. In particular, the goal is indeed to provide a common environment where the localization and data analytics can run as virtual functions, allowing cloud-native applications distributed across edge and core domains. Running such functions on top of a virtualized infrastructure enables a smooth integration of the location based services within 5G networks, being accessible for both network management and vertical customers. In addition, automation in deployment and operation of these virtualized localization analytics services can be achieved by adopting the ETSI NFV Management and Orchestration (MANO) principles [81].

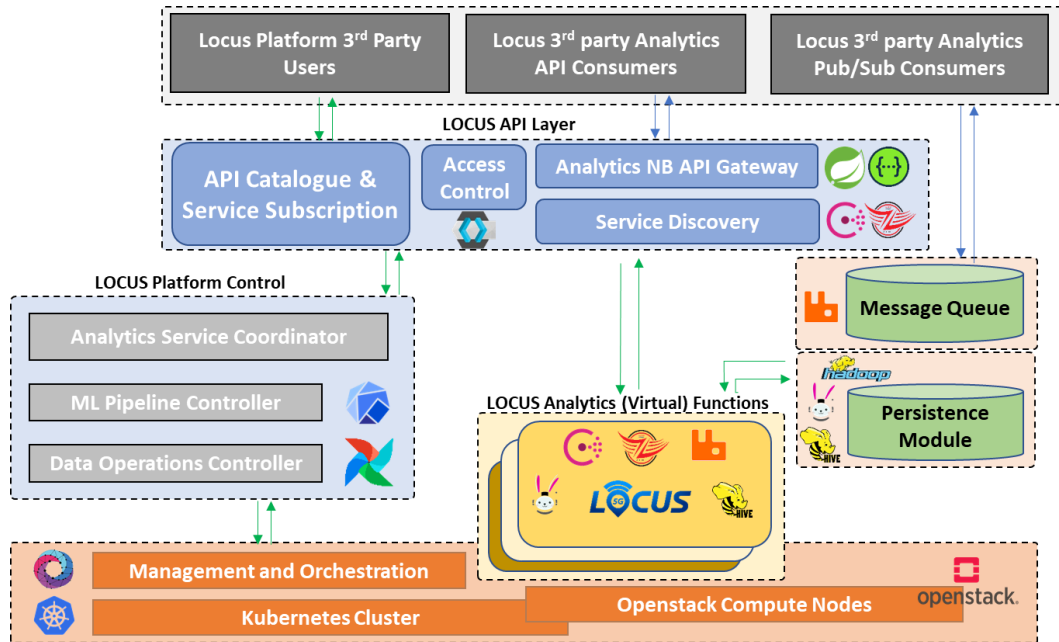


Figure 5.3: LOCUS Platform Architecture Components

As depicted in Figure 5.3, the proposed platform prototype is composed of three main complementary components: the LOCUS API layer, the LOCUS platform control, and the LOCUS MANO, all integrated with the virtualized infrastructure. The API layer represents the northbound interface of the platform and is responsible for providing access to the virtualized analytics functions, ML pipeline services and ML model predictions when they run in the edge/core virtualized infrastructure. On the other hand, it exposes the data they generate as services that can be consumed by external applications (e.g., Smart Network Management). It is implemented leveraging on open-source tools for analytics and data consumption through advanced API gateway and service discovery features (based on Consul and Zuul).

The API gateway and service discovery features are linked with access control features (implemented through Keycloak), and are integrated with a custom catalog and a service subscription module that allows external applications and users to discover the available analytics services and activate them on-demand.

The LOCUS platform control (see Fig. 5.3) allows to decouple the API layer functionalities and the analytics services exposed towards external entities from the complexity of internal analytics functions management and execution, in terms of deployment as virtualized functions, data operations and constraints. It is implemented as a combination of software tools, which integrates custom

applications for analytics service coordination, and relies on open-source tools for analytics service and ML pipeline management and virtualization (such as Apache AirFlow and Kubeflow).

The data exchange among the various localization and analytics functions, required to provide the specific end-to-end service logic, is facilitated by a dedicated data platform, which combines a solution based on RabbitMQ for real-time data streams exchange with a data persistence module based on Hadoop, Hive and Trino. These two solutions enable the analytics services and functions to communicate and exchange data following different paradigms, while supporting real-time and batch processing. For the purpose of the PoC presented in this section, the RabbitMQ message queue module is used as a message broker, which receives messages from a producer (e.g. a localization or analytics functions), elaborates them in a so-called exchange, and route them to different queues, where one or multiple consumers process the message. Here, the exchange of type topic has been used, allowing the use of wildcard matching, where a routing key can define a pattern that matches multiple queues.

The third component of the platform is the MANO, which is implemented on top of the ETSI OSM open-source framework (i.e., the de-facto standard open source NFV orchestration platform), and provides NFV-oriented automation capabilities in the deployment and runtime operation of localization analytics functions and services as Virtual Network Functions (VNFs) and NFV Network Services. It supports fully cloud-native deployments and thus automated instantiation and configuration of localization analytics functions as containerized functions. Each localization analytics function and service part of the PoC presented in this section has been therefore packaged following the ETSI OSM principles and standard NFV descriptors formats, and dockerized to be deployed as container. The LOCUS MANO is tightly integrated with the virtualization infrastructure, which realizes a realistic edge/core computing infrastructure where the localization analytics functions are deployed on demand. For the PoC, the virtualization infrastructure is implemented following a hybrid approach to leverage on de-facto virtualization technologies and support distributed edge/core cloud-native deployments. This allows to match the requirements imposed by the 5G network architecture, which is based on a high degree of network function virtualization that can be deployed at different computing locations. Specifically, it integrates a Kubernetes cluster with an Openstack infrastructure , with the aim of

supporting both traditional virtual machine based services, as well as cloud-native applications more suitable to run at the edge using containerized services.

### 5.1.3 Location-aware failure detection

Context information is starting to be used for network management, i.e. information from different sources (weather, traffic, social events, etc.). Nevertheless, this kind of information is not always available. In contrast, new indicators were generated by taking into account the available cells covering the scenario and the areas where they may interfere each other. With these contextualized indicators [28], it is possible to have additional information about the scenario at low computational cost. To generate them, positioning information is obtained through the LOCUS platform, based on the radio technologies described in Section 5.1.1. This positioning information is generated by opportunistic fusion of ranges from different source technologies [82].

In addition, the cell locations are mandatory to previously compute Voronoi areas. The Voronoi areas are also calculated for the assumption where one of the cells is missing, so overlapping areas refer to the coverage area of cells when their neighbor cells are not working. The cell centers and edges are also considered. The Voronoi areas generated for the desired scenario are depicted in Fig. 5.4.

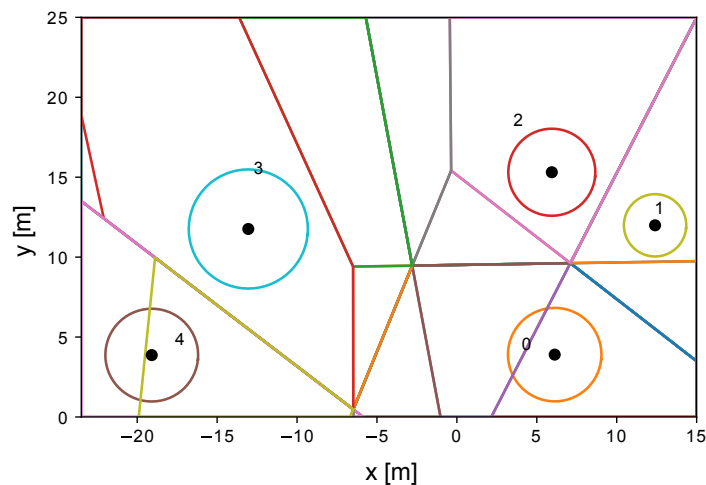


Figure 5.4: Voronoi areas for the scenario under study.

Then, each received sample is related to one or more areas and indicators for each

area are dynamically computed. If the samples are coming from static users, they will always update the same areas, which means the system will be able to detect, e.g. a cell outage, but it will not discover coverage holes. The system will have two perspectives of the scenario: on the one hand, a historical perspective based on all the samples that have been received and processed since the functionality was enabled; on the other hand, it also filters last received samples in order to detect when a network failure has just occurred. A map is generated with the data that have been received, as illustrated in Fig. 5.5, and it is also updated when new samples are collected.

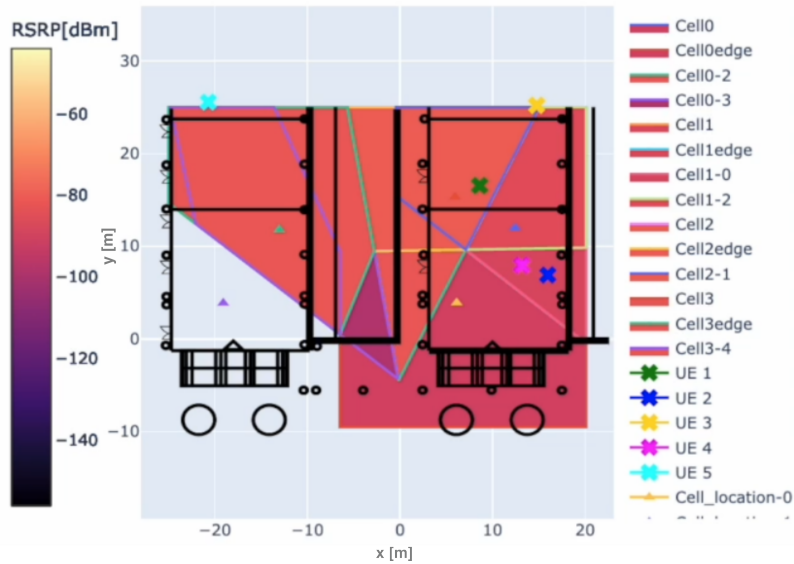


Figure 5.5: Contextualized indicators computed over the scenario.

In the figure, the crosses represent the real-time positions for several UEs, and the triangles refer to the cell locations. Moreover, terminology CellX-Y means area where cell X is influenced by cell Y in case that cell X is not available. It can be observed that there are areas where the coverage is good, and other where it is worse. In addition, there are areas of the scenario where the contextualized area is not plotted, which means there are not recent samples involving that area.

Here, the functionality schema is also based on pipelined Docker containers, as depicted in Fig. 5.2. The first container is in charge of computing and updating the contextualized indicators for each area upon sample receptions. This information is then sent to the LOCUS platform where an ML-aided component returns whether there is any cell outage or every cell is working normally, being the contextualized indicators the input for this component. It is also possible to configure the number of historical samples, i.e., radio metrics provided by UEs together with their location,

that are used to determine the current status of the network. This may improve the accuracy but reduce the reactivity of the system. The last container implements the Graphical User Interface (GUI), which shows the map and the time evolution graph, as well as the output of the ML-aided component indicating the network status.

This component was previously trained with a dataset of users moving around the scenario under different conditions, including normal operation and controlled cell outages. Then, the PDF of the indicators was computed for each area and the system was trained to detect when a cell is not working properly. Figure 5.6 represents an example comparing the normal case with the outage of a specific cell. The figure represents the input features for the ML model of a single case. The model training with the individual cases of other cell outages will feed the model with the necessary information to detect when a cell is not working properly.

The system achieved an accuracy of 90.7% when looking at last historical samples received, being able to detect when a cell is not working properly. However, a refined layer could be added to the system with an additional step consisting on analyzing the historical samples for each area, and then comparing to the last received samples. This would verify the ML model's output is correct (especially when it reports faulty cells), and thus reduce the number of false positives.

In this sense, a more powerful ML model could be trained with additional radio network quality metrics, such as SINR, or RSRQ, being able to provide more accurate results when determining the network status. On the other hand, Voronoi areas could be substituted by other areas, such as hexagons or even areas generated from the beam sets configuration and the cell sectors, both easily available for the MNO.

These functionalities enable new opportunities for the MNO to improve the network management. Their applicability is not restricted to radio quality metrics, but it could be extended to the QoE metrics, which are crucial for the MNO to provide a good service to its customers. However, the regulatory framework should be considered, as the use of location information is subject to strict rules in some countries. In this sense, there are features that would implement localization techniques from the network, as the PRSs or the use of beamforming. The latter enables a beam-based localization with an accuracy high enough for the described functionalities and low enough to potentially comply with the regulations. In any case, the anonymity of the data must be guaranteed. On the other hand, these

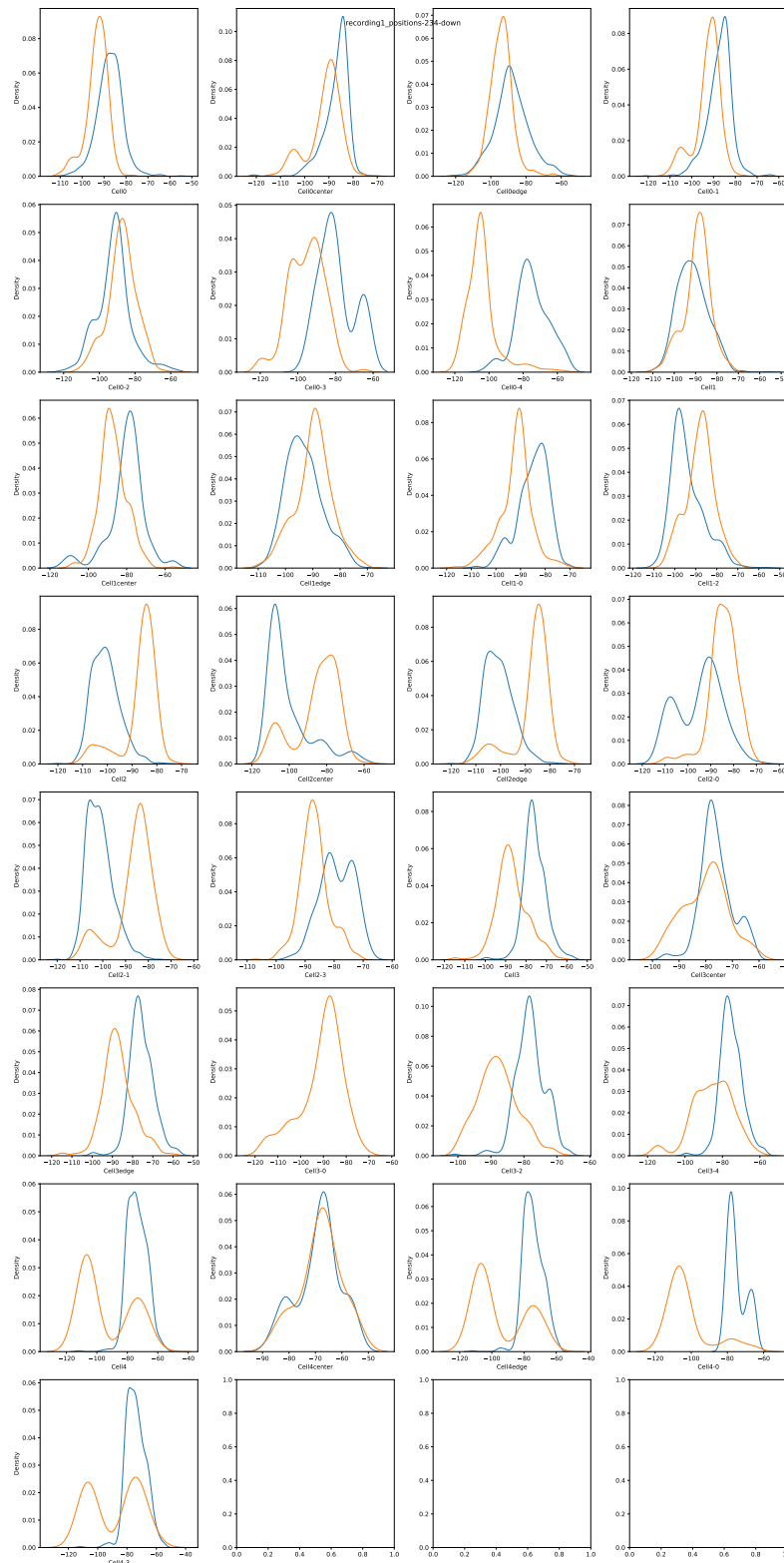


Figure 5.6: Example of PDFs of normal case (blue) and specific cell outage (orange) for all the areas.

functionalities have been tested to receive data in real time, so that they could suggest actions in real time. However, there is a risk when taking actions in real time, so the system should be intelligent enough to properly decide whether a network configuration change should be applied or not in a specific moment.

## 5.2 Zero-Touch Cellular Networks via Next-Generation Crowdsourcing

### 5.2.1 Sources and Characterization

This section reviews the sources of information, covering their main advantages and disadvantages and how they could complement each other to fit into the ZSM scheme. Here, for the sake of clarity, the QoS is defined as the objective quality, measured through different metrics, e.g., packet loss ratio or service delay. In contrast, the QoE is the subjective quality perceived by users, usually obtained through forms under a laboratory environment, and considers the user's expectations and context. The QoE is usually related to the application being used, e.g., freeze frames in video streaming, refers to the delight or annoyance of the user, and it is by definition highly affected by QoS. The QoS comprises the network performance between end devices, but the scope of QoE is broader as it includes the user perception, according to the International Telecommunication Union (ITU) [83].

#### 5.2.1.1 Classic sources

##### Network Metrics

Cellular networks provide performance information classified into events, alarms, counters, KPIs, and traces.

However, these metrics are usually aggregated per cell, so it is difficult to detect specific problems, e.g., they would detect a cell outage that it is generating connection drops, handovers, and capacity problems. Still, it will likely be much more challenging to detect coverage holes, where users cannot even attach due to lousy coverage conditions at specific locations. Moreover, counters and KPIs are typically aggregated into hourly periods, being difficult to identify problems in a short time.

In addition, the network perspective is not enough to identify QoE problems. Thus, the user perspective, as well as context information, may enhance the problem detection and troubleshooting. Here, a user could be registered to the network and report good signal quality but unable to use the service it demands, e.g., videoconferencing.

However, tracing this specific user is not feasible; even if it is reporting bad performance through a ticket, operators cannot devote resources to trace the user.

### Drive Tests

DTs have played a key role in classic network management approaches. They only provide outdoor data but are probably the most precise way to analyze and optimize some network problems, since they have access to RRC layer 3 messages exchange.

Additionally, Minimization of Drive Tests (MDTs) were introduced by 3GPP Rel-10 [84], aimed at collecting radio quality information at UE, and report it to the network [85]. Nevertheless, their drawback is that operators tend to disable them because they may degrade the user's QoS in terms of data rates and battery life.

#### 5.2.1.2 Next-Generation Crowdsourcing Metrics (gCM)

The integration of information from Next-Generation Crowdsourcing Metrics (gCMs) embodies user metrics from lower layers (RSRP, RSRQ, etc) [86] to the application layer (video streaming, web browsing, etc), into the ZSM offers several advantages. It will allow the network to optimize user experience autonomously, as well as to tailor its services automatically according to user demand patterns. Altogether, this will enable in-depth troubleshooting and problem detection, reducing downtime and the need for human intervention. Lastly, real-time, automated resource allocation based on user equipment data will incorporate efficiency into automation.

Nevertheless, this work focuses on the analysis of both mobile and stationary gCMs obtained from real cellular network users. Figure 5.7 illustrates a scenario where both UE-side Network-side metrics are collected. They together power the proposed ZSM framework, which is aided by ML techniques over both data types. The components of the classical ZSM architecture are represented in grayscale, while the novel gCMs components and techniques are colored.

Source	Granularity		Cost		Variability
	Temporal	Spatial	Computational	Operational	
Network metrics	↑	↓	↕	↕	↕
Drive Test	↕	↕	↓	↕	↓
gCM-M	↑	↕	↓	↕	↕
gCM-S	↕	↓	↓	↑	↓

Table 5.1: Characteristics of Sources of Information

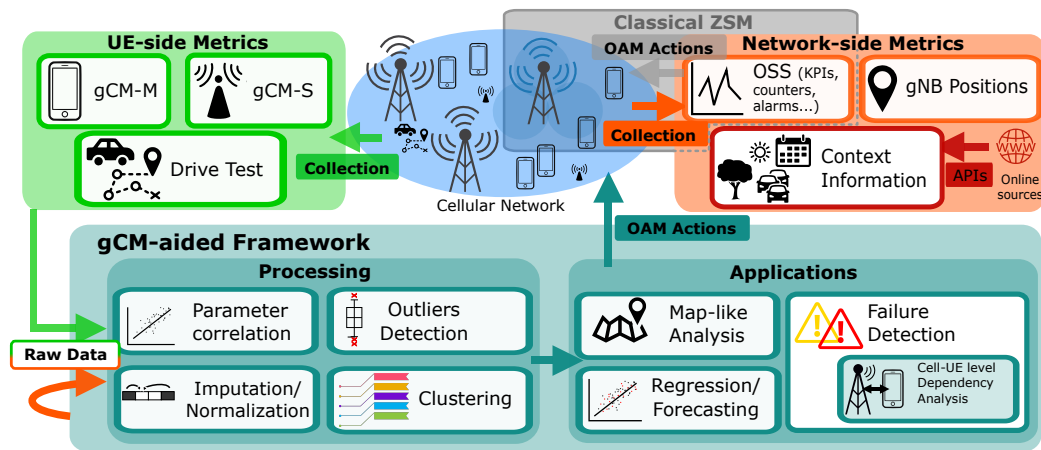


Figure 5.7: UE-driven ZSM management framework

### Mobile Next-generation Crowdsourcing Metrics (gCM-M)

This information is collected from the application layer; it has access to the Operating System (OS) and thus asks for information from the radio modem. This way, data can contain information about only low-layer metrics or both low-layer metrics and Key Quality Indicator (KQI). Thus, the samples always contain low-layer information: timestamp, radio information (e.g., band, RSRP, RSRQ), and location information. Additionally, these samples comprise device details (brand, model, operating system version, enabled features...), and operator information (e.g., Mobile Country Code (MCC) and Mobile Network Code (MNC)). The collection of this type of data is cost-effective since the metrics are continuously being taken, and it would only require storing them, without triggering extra measurements. The only task needed is to save the data to a file

and report it within a specific period. In this sense, these data can be collected with high temporal granularity. Although computing the position for localization needs some processing, it usually takes advantage of other applications that use the location for other purposes. e.g., real-time location sharing with friends. In fact, when the GPS module is being used by any application on the terminal, the temporal granularity could increase at zero cost, e.g., while using navigation to get to a place. In this case, the collected data is comparable to a simplified DT. These data have to be properly anonymized in order to respect privacy laws. Still, it is helpful since it aims to exploit the data to acquire a complete vision of the network performance from the final users' perspective.

On the other side, there is a second type of data that includes service-specific KQI by performing experiment tests. KQIs directly refer to service performance that users experience while using. Experiments consist of performing some short actions that are directly related to what a user may need, e.g., a ping test or a small file download or upload. Triggering these events is less efficient in terms of battery and mobile data usage. Hence, their temporal granularity is typically lower. Two approaches are envisioned here: keeping limited the number of samples with QoE information or using regression techniques to estimate QoE metrics using low-layer metrics as input. This is described in Section 5.2.2. There are several experiment types configured with different periodicity according to the resources they use. They are designed to be transparent for the users but also to cause the minimum impact on both the device and the network: for the low-layer information, the network burden is zero since radio quality metrics collection does not imply network traffic; for the KQI information, the network burden is reduced, since the amount of traffic that is transferred is minimal, and the experiments are scheduled to be performed while the user is actively using the network for other purposes.

However, the main drawback of these data is the diversity of users. Each user owns a different device, with specific capabilities, radio chipset, and processor, as well as different OS versions. This results in different behaviors in the same data collection application or library on different devices. These differences were appreciated during this work, and some analyses were performed by filtering these characteristics.

### Stationary Next-generation Crowdsourcing Metrics (gCM-S)

An additional source of information is the use of probes (named beacon), that are deployed on specific locations with the aim of acting as UEs that perform typical users' tasks. Beacons are considered in between UE Apps and DTs. They can collect richer information than UE apps since power and data usage is not a constraint, as it happen with DTs equipment. Thus, their temporal granularity is notably higher. On the contrary, they are usually in fixed positions, so their spatial granularity decreases. Their main advantage compared to DTs is their cost, since they do not need and engineer to perform a moving test, as well as the fact that they are usually sited indoors. The indoor coverage estimation is usually challenging because DTs do not commonly include indoors, but UE apps and beacons are potent alternatives to overcome this. Thus, not only department stores or stadiums but also cellular network providers may be interested on deploying beacons on their premises, since it will enable performance analysis from the user's perspective. This approach has also been studied in the literature with different perspectives, e.g., to monitor social events' impact on a network [34]. Moreover, Internet of Things (IoT) devices are also envisioned as a source of network information in [33]. They would show less variability that UE directly measures: on the one hand, due to the fact that the beacons are commonly stationary; on the other hand, the device hardware capabilities of the beacons are almost equal among them. Also, they do not depend on the user's usage as it happen with the UE application data. Parameter correlation findings are also clearer regarding beacon data, as shown in Section 5.2.2.

In addition, there is another kind of metric that is becoming important for network management: the information from the context, e.g., traffic, social events, weather... By combining contextual information with the rest of metrics, some problems can be detected when unusual behavior is identified over the KPIs [1].

In conclusion, Table 5.1 summarizes the different sources of information, where advantages and disadvantages are highlighted in green and red, respectively. It shows that each source has negative points, regardless of the effort that is needed to post-process the retrieved information. However, UE apps provide great advantages at low cost, except for the high variability, given the different characteristics of the devices that are used. They can play an important role towards ZSM, as described in the next section.

For the remainder of this section, UE-side metrics will refer to both UE

application metrics and beacon metrics, since drive test data are not deeply treated in this work.

## 5.2.2 Zero-Touch Management Framework

The proposed framework for the acquisition of both sides of the network and the exploitation of the data towards ZSM is illustrated in Figure 5.7, whose components are detailed in the following subsections.

Firstly, although we distinguish between data collected from UE side and non-UE side, the framework is based on the gCMs, being able to benefit also from classical non-UE metrics if they are available. In this sense, Cell-UE level dependency analysis is considered an optional component that could enhance the results. This framework is able to process data from different sources, which implies different formats (Raw data in Fig. 5.7), so they are formatted and internally stored by following a common structure. This format allows the data retrieval by the different components and applications of the system.

Consequently, these data are then passed to the processing block, where there are different mechanism that can be applied on the data in order to extract relations between parameters, clean the data from anomalies, and prepare them to be used by the network management applications. The applications block is the last step within the framework as it provides information on the past, current and forecasted network states. The use of real-time inputs for the framework is possible since the users will only need to carry their UEs with them. The framework components have been applied on real data, and they are described in detail in the following subsections.

### 5.2.2.1 Data Processing

As described above, the data processing block is key within the framework. The UE-side data is noisy by nature, since it comes from different devices and people, which means each sample is likely singular. At the same time, this randomness of conditions where users can report information leads to a wealth of data, which is beneficial while it requires high complexity processing. This block is composed of multiple functionalities: parameter correlation, imputation/normalization, outliers detection, and clustering.

### Parameter Correlation

Firstly, classic pre-processing correlation techniques are applied. They provide an initial analysis of the linear and non-linear correlation coefficients. Several insights were obtained from the Pearson correlation coefficient (See Eq. 5.1), i.e., a measure of linear dependency between random variables, which is illustrated in Fig. 5.8.

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}} \quad (5.1)$$

It shows that the QoS metrics with higher correlations are different between DL and UL rates. This means that Signal-to-Noise-Ratio (SNR) is the most important metric for estimating DL rate while RSRP is the most important for the UL rate estimation. In the figure, some observations are direct, such as the incorrelation of the WiFi connection (WifiConnected). But others will need further analysis, for instance, the month when the sample is taken (LocalTime\_month), which could be related to the season, but in this case, was then actually related to the number of available samples.

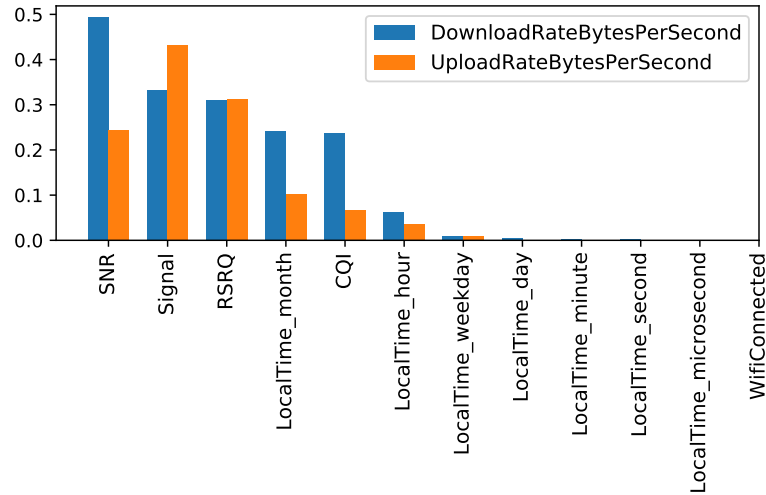


Figure 5.8: Pearson correlation coefficient between QoS metrics and the DL and UL rates.

### Imputation/Normalization

Imputation consists on using the existing samples to generate artificial values for missing samples. This is performed on the QoS samples since they are more robust. Here, different techniques have been considered, from computing the mean of the

existing samples as baseline to using decision tree estimators. These techniques can increase the size of the dataset. Then, the synthesized QoS samples are also used as input for regression techniques, that are described below.

On the other side, the QoS metrics that are present in the samples are miscellaneous. Here, there are mainly radio metrics and device information, but also other metrics such as the status of the screen or whether some services are enabled or disabled. This implies that normalization of the data is required, given the fact that different metrics use different ranges of values. Figure 5.9 represents the enhancement in terms of  $R^2$  score (i.e., the predictive performance of the model), when imputing samples using an *Extra-Trees* regressor with different normalization techniques. *Extra-Trees* regressor consists of an ensemble learning algorithm that constructs multiple decision trees and combines their outputs. In the figure, it can be observed, as expected, that some metrics cannot be properly imputed (e.g., battery\_level, is\_screen\_on). However, this is not a problem because they are not the intended metrics for the proposed system.

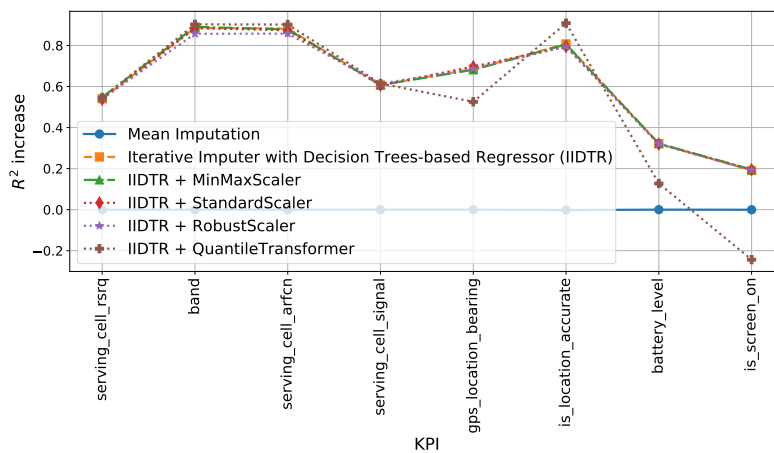


Figure 5.9:  $R^2$  increase of different imputation techniques in comparison to Mean Imputation technique for different a set of KPIs.

### Outliers Detection

Here, the data collected through UE application depends on many factors. The brand, device model or operating system version may influence not only the radio indicators (QoS) but also the experiment results. UEs often get frozen, receive calls, or are asked by the users to open an exigent application while they are performing some other tasks, that is, metrics collection. This may lead to extreme values reporting while the network conditions are not really degraded. It can also occur

that the resources or tokens needed by the measurement collection application are in use or blocked by any other application, for example, an OS optimizer or cleaner application trying to free resources. In this case, almost all the data collected by a specific UE may be corrupted. These abnormal values are called outliers and they usually add noise to the analysis. Its detection and deletion become key, especially for automatic processing. However, they could also be the more apparent symptoms for detection algorithms, in which case deleting them would be detrimental for the system.

### Clustering

Furthermore, clustering techniques aim to find similarities between samples. Two types of clustering are envisioned: position-based and metric-based. In the first case, it is possible to find zones where people are usually very close to each other, e.g., a shopping mall or a crowded downtown street. However, the reported cluster metrics may actually be suitable when some users are being rejected by the network or the cell. The metric-based case aims to identify users that are reporting similar network conditions and, therefore, similar QoE. This allows to find users that may complain to their operator about their cellular services due to bad experience, and try to analyze the root cause of the problem, also by exploiting the localization information.

#### 5.2.2.2 Applications

The main aim of the proposed framework is to apply the information towards the enhancement of the network performance. Therefore, different applications have been identified and tested with real data. There is a wider range of possibilities when considering UE-side metrics for network management. A set of them are described below, together with the insights obtained from results.

#### Map-like QoE Analysis

In addition, map graphing is helpful in representing the data. gCMs allow to know the location of samples, so their representation on a map may help to find areas with useful information from an operator perspective, e.g., poor coverage. Figure 5.10 illustrates a map containing the described techniques. It represents imputed KPIs

(RSRQ), as well as the real and estimated KQI samples for the download time of a 2 Mb file experiment. The latter have been obtained by using ML-based techniques using the gCM low-layer metrics as input. Then, clusters can be represented over the map in order to geographically analyze their distribution and extract information of interest towards optimization.

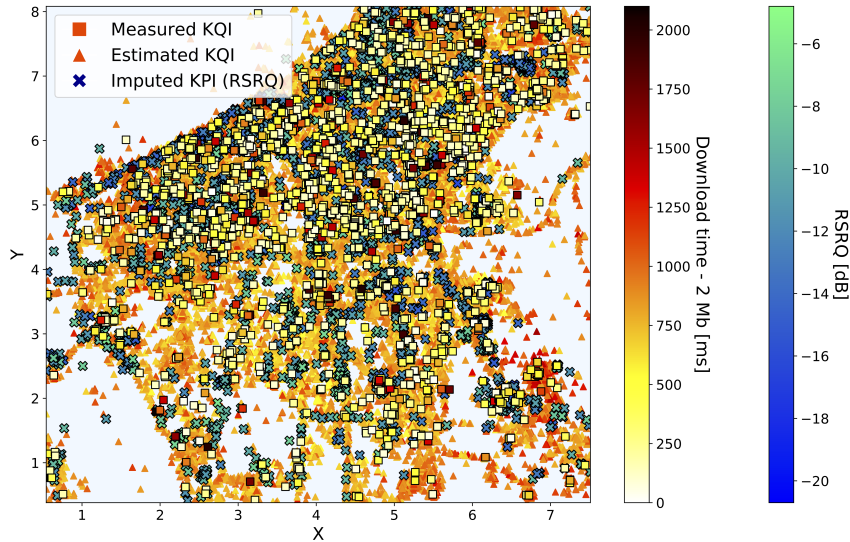


Figure 5.10: Map with original and estimated data for QoS and QoE.

Besides, the radio maps may assist a wide variety of applications, such as proactive interference management, resource provisioning and network planning, and spectrum security and surveillance [87].

### Regression

Besides, regression is a valuable application given the fact that it enables the QoE estimation, that is, KQIs based on QoS metrics. This has been widely addressed in the literature [88], together with service-oriented approaches (video transmission, cloud-gaming...) [89, 90, 91]. As commented before, users only care about the experience (QoE), but not about the service (QoS). Thus, here is where operators need to make an effort. If ML-based models can properly estimate the QoE, metrics that operators do not usually have, they will really take advantage of them. This means a big step towards the efficiency, which is one of the objectives for future cellular generations.

QoE estimation enables the possibility of offering better performance to users as well as turning cells to sleep when the conditions are good enough for the

number of connected users. This is envisioned by taking into account the localization information of users together with the location of points of interests. In addition, context information would enhance these procedures by providing, e.g., social events information or even cellular metrics predictions [32].

### Failure detection

Finally, the outputs of the described applications are beneficial regarding failure detection. From the regression of QoS/QoE indicators on areas where there are no available data for the coverage hole identification over a map, this gCM data becomes crucial. Therefore, the combination of map-like analyses and regression techniques serves as input for the failure detection. Failure detection is approached by first defining geographical areas, averaging the samples within each area, and then comparing the values of different parameters with respect to the normal case if known, or to the rest of the areas where a similar number of samples are available. In this approach, an area has fewer samples than others can lead to inconsistency on the failure detection mechanisms. To overcome this, data imputation is intended to be performed during the processing phase.

Moreover, dependency analysis between cell and gCMs is envisioned from the operator perspective. Operators are the only ones that can filter gCM samples to compare those connecting to their network. Thus, they can relate the historical cell metrics or statistics with the gCM data. This way, they are able to detect whether a problem detected on the gCMs is really a network problem or it was just related to a certain user(s), or location (e.g., inside a building).

### 5.2.3 Open Challenges

The previous results have shown how the described techniques can be applied, as well as the obtained results. However, there are still some challenges that to be overcome for the proper exploitation of the proposed framework.

- **Standardization:** Although these techniques could fit in the current 5G architecture, there is not a standardized solution for UE application or beacon software. Thus, solutions are currently being individually applied by third parties. While using this individualized approach, it will not be easy to integrate it with the OSS. In contrast, if this was standardized, gCM could

be enabled or disabled by operators and per specific area when needed. Or they could even be enabled on users sequentially to get rich information without affecting the overall performance. Similarly, the standardized solution must ensure the privacy of the users by avoiding sending identification information, thus preventing potential privacy leaks. The purpose of the gCM is to provide information overall, not about specific users, so no identification is required.

- **OpenRAN Compatibility:** When looking towards the OpenRAN paradigm, the exploitation of the UE-based metrics is envisioned as a rApp which is running on the Non-Real-Time (RT)-RIC. RIC is a software-defined component of the OpenRAN architecture that is responsible for controlling and optimizing RAN functions. It is a critical element that enables disaggregation strategy as well as multivendor interoperability by enabling the onboarding of third-party applications. Here, OpenRAN integration would be feasible, but it is not yet mature enough on real deployments.
- **Data heterogeneity:** Regarding the UE application metrics, the most important challenge is to reduce the gap in terms of performance that exists between different devices. The current devices' heterogeneity introduces noise into the ML algorithms. This sometimes makes them impossible to work as expected. Besides, UE applications are not perfect, so bugs may derive into unreal samples. Here, requirements should be defined in order to distinguish whether a sample is considered or not. A possible solution regarding this issue is to consider different device categories, so that performance metrics can be compared to similar devices in a close location. The concept of similar devices ideally refer to the same model, but otherwise, the same chipset, device vendor, OS version, or other metrics previously identified as differentiating.
- **Real-time Filtering** There are also risks when using real-time collected data as input for the system. When certain user(s) enters a building, namely an indoor location, their UE reported data can be dropped significantly. These data should be filtered to avoid false positives in the failure detection mechanisms. Here, sensors available at UE can jointly be used for estimating whether users are indoor or outdoor. However, it could also happen due to a network problem. The latter case should require applying failure management actions on the network, but not the earlier. Then, it would

require a really refined problem identification criteria, able to distinguish problems and normal operation.

- **Localization techniques:** Additionally, gCMs location is usually based on GPS, which is not suitable in indoor scenarios, and indoor positioning alternatives are generally not accessible for the users because they tend to be private deployment (e.g., UWB-based deployments). This means that it is difficult to determine whether users are indoors or outdoors, and consequently whether a massive drop on the QoS/QoE data should be labeled as a network problem occurrence. However, 5G-based positioning will overcome this problem in indoors by using specific signals, for example, PRSs.

# Part III

## Achievements

# Chapter 6

## Conclusions

### Content

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This chapter summarizes the main outcomes and conclusions of this thesis. Firstly, Section 6.1 reviews the objectives chased in this thesis, focusing on the main contributions of each of them. Secondly, Section 6.2 enumerates future research directions that can be pursued based on the results obtained from the work performed. Finally, Section 6.3 lists the publications and projects related to this thesis.

## 6.1 Contributions

This thesis aims at the provision of novel techniques for network management, adapted to the 5G technology and prepared for the future. For this purpose, the novel features and requirements have been studied in depth, and the main challenges have been identified.

Beamforming has been identified as a candidate technology where network management needs to focus on. Therefore, this thesis provides an analysis of the beamforming performance, as well as some techniques to improve its operation.

Lastly, this thesis has approached the inclusion of two additional sources of information for network management: user-side metrics and localization information. A proposed framework has been developed and tested on real equipment.

The main contributions presented in this thesis, given the proposed objectives, remain as follows:

- **Objective 1: To explore the novel RAN features in 5G.**
  - Firstly, the current status of 5G development is assessed in order to identify which novel features may potentially lead to problem situations.
  - Classic network OAM procedures have been reviewed from a failure management perspective, as well as the 3GPP updates with respect to the previous version of specifications.
  - Three problems have been validated under simulation, demonstrating the relevance of location and speed awareness for the management of such failures. They are the mmWave outage, the beamforming configuration, and the cross-link interference. They settled the basis for the development of the rest of the thesis.
  - The configuration parameters related to mobility management have been identified, especially those that are left to the implementation. Here, beamforming has introduced new parameters, which are expected to be critical for network management.

- **Objective 2: To propose innovative techniques to address the features and network problems introduced in 5G.**
  - Novel KPIs have been defined, leveraging the information obtained from the beamforming-related counters. These KPIs provide useful insights for network management, as well as from a failure detection perspective.
  - An ML-powered localization technique has been introduced, where there are no costs in terms of overload and energy usage. While the accuracy is not comparable to GNSS, it is a potential method for the cases where GNSS is not available, either from the network side or at indoor scenarios from UE side.
  - A set of conditions has been proposed to enrich beam switching triggering criteria at mmWave. This technique aims at optimizing average radio quality as well as reducing the number of beam switchings and ping-pong occurrences.
  - The idea of reducing CSI-RS when a user is stationary was pointed out based on the mmWave results so that location information could help to decide how much resources are allocated to CSI-RS.
  - The results of measurement campaigns conducted in the industrial scenario suggest the need for specifically configuring beamforming parameters depending on the scenario, especially at mmWaves.
  - Processing steps for Next-Generation Crowdsourcing Metrics (gCMs) as well as potential applications towards achieving ZSM have been derived from the analysis performed over real data from commercial users.
- **Objective 3: To analyze the performance of beamforming feature and proposed network management solutions on real deployments.**
  - The potential of the 5G SA technology has been revealed by means of a commercial equipment infrastructure deployed at the UMA campus.
  - The performance of 5G mmWave has also been evaluated in a real scenario at AAU campus. Here, beamforming is studied in terms of radio quality and reduced number of beam switchings in a realistic mmWave industrial scenario where a user is moving. This is relevant for critical assets within the industrial use case since they are sensitive to latency or outages.

- The 5G SA and the mmWave measurements have been made available to the research community by uploading the collected datasets.
  - Regarding the framework integration, the behavior of the different components working together over a virtualized infrastructure was analyzed, assessing the feasibility of the approach even when the management algorithms platform and the physical scenario were located in different countries. The tested functionalities have shown promising results with regard to exploiting location information in an indoor scenario.
  - Classic network management has been compared to the presented framework incorporating gCMs. For the analysis, real Mobile Next-Generation Crowdsourcing Metrics (gCM-Ms) and Stationary Next-Generation Crowdsourcing Metrics (gCM-Ss) have been used. The different applications of this kind of data have been reviewed and evaluated, including their advantages and disadvantages.
- **Objective 4: To develop a framework integrating user-side metrics and localization for network management.**
- Insights on how beamforming procedures can be optimized have been retrieved from the work performed at mmWave, where the location information plays a key role in this aim.
  - The design and implementation of a real-world location-aware network management infrastructure have been conducted, where network management functionalities leverage location information received in real time. Location information has been demonstrated to be crucial for network management, even in an indoor Sub-6 GHz scenario.
  - The use of gCMs towards future ZSM has been reviewed, and a novel approach for their processing and application in network management has been proposed.

Additionally, the transversal objective of deployment of real infrastructure has been successfully accomplished. Here, the configuration of the equipment to be integrated as part of the UMA infrastructure, support to the vendor configuration team, remote access, support to the upgrade of the equipment, servers installation

to offer local services, and assistance provided to the rest of the researchers aiming to use the infrastructure, have been some of the tasks performed.

## 6.2 Future work

As a result of this thesis, several lines of research and potential applications have been identified. These comprise not only further improvements supported by the present research but also additional developments and wider applications arising from it:

- The beam switching performance is envisioned as a potential topic for optimization in the O-RAN paradigm, where the actions on the radio parameters can be near-RT or non-RT thanks to the RIC. The development of an xApp to manage the beam switching configuration in real-time is envisioned.
- The performed analysis at Sub-6 GHz from the network side can be extrapolated to mmWave, where the number of switchings is expected to be higher, and its management is more critical since it can lead to connection drops.
- The beam-based ML-powered localization technique can be enhanced either by using different beam sets or metrics as input or by improving the ML algorithms, as well as extended to mmWave.
- The KPIs definition proposed is envisioned to be extended with other metrics. Novel metrics will also be unlocked when the RIC is fully deployed and operable.
- The joint analysis of proposed KPIs with other traditional KPIs will provide a richer overview of the network performance.
- A multi-cell analysis is also intended to be performed, where the defined KPIs will provide a two-dimensional direction of movement for the users. From a multi-cell perspective, handover-related KPIs can be considered, providing a richer overview of the users' movement.
- The main outcomes from the evaluation done at mmWave are applicable to other scenarios. Here, an in-depth analysis of the beamforming operation in an outdoor scenario is envisioned as the next step. In an open area, the distance to the BTS is more variable, and beamforming analysis has not been realized to the best of the authors' knowledge.

- The beamforming study done at mmWave had restricted access to the network side. The possibility of changing network configuration parameters related to beamforming will close the loop to understand how the different configurations may affect the beam switching performance, including either changes in the beam set configuration or the beam switching thresholds, among others.
- The exploitation of the localization information is also open to future research, where multiple additional applications can be fostered.
- The location-based functionality could be easily extended to be based on other metrics, including QoE, in order to be able to identify other issues related, e.g., to network capacity or congestion, in a particular situation or area. The proposed architecture supports this extension, as it is designed to be flexible and scalable and to support the integration of new functionalities.
- Regarding data processing, a wide variety of ML techniques could enhance the achieved performance. Besides, additional metrics could be added both from UE and network sides.
- Finally, although various applications benefitting from user-side metrics were presented, the proposed framework is open to novel applications that could be developed based on the gCMs.

## 6.3 Research Activities

### 6.3.1 Exhibitors

The work's contributions have also been showcased in the form of exhibitions at technological conferences and events. These exhibitions have allowed the exchange of innovative approaches and research results of this thesis, facilitating a valuable exchange of knowledge and experience with the academic and professional community.

As a result, the work's various contributions have been presented at the following events:

- Mobile Week Málaga 2021, organised by Palacio de Ferias y Congresos de Málaga (FYCMA) in Málaga (Spain), December 2021.

- H2020 LOCUS project booth exhibition at EuCNC & 6G Summit 2022, June 2022, in Grenoble (France).
- European Commission (virtual presentation), as part of final evaluation of H2020 LOCUS project, January 2023.

### 6.3.2 Related projects

This thesis was funded by the Ministry of Science, Innovation, and Universities through the programme: Ayudas para la Formación de Profesorado Universitario. Grant agreement FPU20/02863.

The work developed in this thesis has contributed to the following projects:

- **LOCUS**: LOCalization and analytics on-demand embedded in the 5G ecosystem, for Ubiquitous vertical applicationS. Grant agreement No. 871249, receiving funds from the European Union’s Horizon 2020 research and innovation programme.
- **MUSE**: MUSE - Massive User Experience Assessment and Prediction for Mobile Networks. Project number UMA-CEIATECH-15, receiving funds from Junta de Andalucía (Campus de Excelencia Internacional Andalucía TECH) and European Regional Development Fund (ERDF).
- **MAORI**: Massive AI for the OpenRadIo b5G/6G network. Project number TSI-063000-2021-75, receiving funds from Ministerio de Asuntos Económicos y Transformación Digital and European Union - NextGenerationEU within the framework “Recuperación, Transformación, y Resiliencia”.

### 6.3.3 Research stays

This thesis involved a stay as a visiting researcher at Wireless Communication Networks (WCN) Section, Department of Electronic Systems, at Aalborg University (AAU), between February and June 2023. This stay was supervised by Associate Professor Troels Bundgaard Sørensen and Professor Preben Mogensen. Preben Mogensen is a Bell Labs Fellow at Nokia and also holds a part-time Professor position at Aalborg University, Denmark.



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# Part IV

## Appendices

# Appendix A

## Summary (Spanish)

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Este apéndice contiene un resumen en español del trabajo realizado en esta tesis.

## A.1 Motivación

La llegada de las redes celulares ha revolucionado la manera en la que las personas se comunican, trabajan y, en general, viven. Las redes móviles hicieron posible una comunicación ubicua y siempre conectada, que ha cambiado la forma de vivir de la población, desde las interacciones sociales hasta los aspectos económicos de la sociedad. Esto ha sido posible gracias a la continua evolución de las redes móviles así como su despliegue en una gran parte del mundo.

Sin embargo, cada generación celular ha traído consigo nuevos desafíos, oportunidades y requisitos. Empezó con las llamadas de voz, que evolucionaron hacia servicios de datos, y que ahora se están convirtiendo en servicios complejos, como la realidad extendida (XR), el juego en la nube (CG) o la conducción autónoma. Desde perspectiva económica, han habilitado funcionalidades clave para los negocios, desde las plataformas de comercio electrónico, los servicios en la nube, el internet de las cosas (IoT) o la Industria 4.0. No obstante, cada generación móvil ha conllevado un esfuerzo significativo por parte de los operadores celulares (MNO) para desplegar los nuevos elementos de la infraestructura y adaptarse a los escenarios físicos, por ejemplo, para instalar nuevos emplazamientos que provean la cobertura y capacidad necesarias para los nuevos casos de uso (UCs) en la mayoría de las áreas donde ya habían desplegado la generación anterior. A pesar de ello, los ingresos del servicio móvil a nivel global han crecido en torno al 15% en los últimos 3 años [18].

La importancia de las redes móviles está indicada en los informes sobre el uso del tráfico, donde se muestra un crecimiento exponencial del tráfico de datos móviles consumido por los usuarios. El tráfico de datos móviles total ha crecido de 10 EB en el primer cuatrimestre de 2017 a 145 EB en el primer cuatrimestre de 2024, considerando tanto el tráfico de subida (UL) como de bajada (DL) [19]. Este crecimiento ha sido impulsado por el incremento de el número de suscripciones móviles así como el aumento del consumo de datos por suscripción. Además, la adopción de cada generación es más rápida que la anterior. La especificación de 5G-NR fue completada por el 3GPP en 2017, y el número de suscripciones 5G ha

crecido notablemente desde entonces, habiendo añadido 160 millones de suscripciones 5G durante el primer trimestre de 2024, superando un total de 1700 millones de suscripciones 5G en todo el mundo [19]. Las suscripciones 5G se han contabilizado cuando los dispositivos soportan NR, según la Release 15 de 3GPP, y se han conectado a una red 5G. El número de suscripciones 5G se espera que supere los 5600 millones en 2029 [19].

En este sentido, el crecimiento de usuarios, la aparición de nuevos casos de uso exigentes, y la heterogeneidad de los escenarios han estado en el punto de mira desde la perspectiva de gestión de la red. La gestión de red es un aspecto clave para que los MNO puedan asegurar la calidad del servicio y ofrecer una experiencia sin cortes para el usuario. La automatización de las tareas de orquestación y gestión de la red (OAM) han dado lugar al concepto de redes autoorganizadas (SON), que fue definido inicialmente en 2008 [20]. El paradigma SON incluye autoconfiguración, autooptimización y autocuración, y tiene como objetivo reducir los gastos operacionales (OPEX) mediante la minimización de la intervención humana, así como mejorar el rendimiento de la red. Debido a esto, la literatura sobre este tema es extensa [21, 22, 23, 24, 25].

Sin embargo, la tecnología 5G introduce nuevas características, como nuevas bandas de frecuencia, técnicas de conformación de haces (*beamforming*), asignación de mayor ancho de banda, uso de multiplexación por división en tiempo TDD, y nuevos elementos en la arquitectura de red, entre otras. Las características mencionadas introducen una nueva dimensión de parámetros que pueden ser configurados, haciendo la gestión de la red una tarea más compleja.

Los sistemas clásicos de OAM se basan en la información de la red, por ejemplo, los indicadores clave de rendimiento (KPI) o los contadores de red que se recogen de los elementos con una frecuencia baja (normalmente, cada hora, o con un máximo de 15 minutos). Esto significa que la capacidad de reacción de la gestión de red es limitada, y también la perspectiva de la red por sí misma, sin la consideración del lado del usuario.

En este contexto, existen fuentes de información adicionales, como la localización del usuario [26, 27, 28, 29] y la información de contexto [30, 31], que se han convertido en una parte fundamental para los que sistemas OAM puedan tomar decisiones más fundamentadas. La información de contexto incluye aspectos externos, como eventos sociales [32], que enriquecen la información disponible para la gestión de red.

Además, la recolección de métricas del lado del usuario se considera también una fuente de información de cara a la gestión de red, ya que proporciona una perspectiva directa sobre la experiencia del usuario [33, 34, 35]. Este concepto podría reemplazar los costosos *Drive Test (DT)* que han sido utilizados tradicionalmente por parte de los MNOs para evaluar la red y encontrar problemas.

Por otro lado, el uso de las técnicas de aprendizaje máquina (ML) tienen una enorme capacidad para manejar grandes cantidades de parámetros de forma simultánea. Los algoritmos de ML se utilizan para diferentes propósitos en la literatura: análisis de las causas raíces [37]; gestión de fallos de celda [38]; o gestión de autocuración en entornos ultra densos [30].

Por tanto, las consideraciones anteriores ofrecen un amplio abanico de oportunidades de investigación basadas en las nuevas características de 5G, las nuevas fuentes de información, o las técnicas de ML, junto con los requisitos de usuario más exigentes y la necesidad de una red flexible y adaptable a los nuevos casos de uso. Esta tesis desarrolla nuevos enfoques para suplir las necesidades descritas, y se centra en mejoras que pueden ser aplicadas en el contexto de 5G y futuras generaciones, donde el paradigma de la *Radio Abierta* (Open RAN (O-RAN)) [39, 40] está previsto como el siguiente paso en la evolución de las redes móviles, basándose en el *software* de código abierto y la interoperabilidad de los diferentes fabricantes.

## A.2 Preámbulos

Esta tesis ha sido llevada a cabo en el grupo de investigación *Mobile Networks Lab (MOBILENET)*, perteneciente al Instituto Universitario de Telecomunicaciones (TELMA, TIC-102) de la Universidad de Málaga.

El grupo *MOBILENET* surge en el año 2000 de la colaboración del grupo TIC-102 con Nokia Networks en la creación del Centro de Investigación de Comunicaciones Móviles, establecido en el *Parque Tecnológico de Andalucía* (PTA) en Málaga. Este centro estaba compuesto por más de 50 empleados, profesores de TIC-102 y personal de Nokia con experiencia.

Así, *MOBILENET* se encuentra especializado en la investigación y desarrollo de algoritmos SON para las redes de comunicaciones móviles. En este aspecto, uno de los proyectos iniciales llevados a cabo por el grupo, fruto de la colaboración

con Nokia Networks, consistió en el desarrollo de una herramienta automática de solución de problema para la red de acceso radio (RAN). Esto estableció algunas de las bases para la fusión de datos reales de redes celulares junto a la experiencia de ingenieros en una herramienta automática de solución de problemas. Más tarde, esta idea ha sido potenciada con la aplicación de técnicas de ML a las herramientas existentes.

Desde entonces, el grupo *MOBILENET* ha participado como parte de consorcios con compañías nacionales e internacionales en el marco de múltiples proyectos de investigación. Entre los más recientes, destaca el proyecto *H2020 LOCUS*, enfocado en el uso de localización y el análisis de datos como parte del sistema 5G para el desarrollo de aplicaciones verticales ubicuas.

Las investigaciones realizadas por *MOBILENET* se llevan a cabo dentro de la Universidad de Málaga [41]. Esto permite la realización de pruebas experimentales sobre una red 5G privada, compuesta por 6 celdas interiores, 3 exteriores, y un core completo virtualizado (5GC). Esta infraestructura está basada en equipamiento comercial y aislada de la red comercial, lo que permite realizar cualquier cambio de configuración sin la necesidad de obtener permiso por parte de los operadores de red.

### A.3 Desafíos y Objetivos

El objetivo principal de la tesis es proponer mecanismos novedosos de gestión de redes para la tecnología 5G y posteriores. En particular, se abordarán los nuevos retos que nacen de la introducción de nuevas funcionalidades para dar soporte a los Use Cases (UCs) innovadores. Del mismo modo, este trabajo pretende extender la automatización de la red celular al siguiente nivel, siendo capaz de soportar la última y las venideras generaciones de redes celulares.

Los escenarios de las redes celulares han evolucionado mucho en los últimos años, impulsados por la introducción de nuevos servicios y la necesidad de dar soporte a una amplia gama de dispositivos. Esto ha llevado al desarrollo de nuevas arquitecturas y tecnologías de red más flexibles y adaptables a los requisitos de los servicios. La figura A.1 representa un escenario 5G típico. En este escenario coexisten dos tecnologías de acceso radio (RATs): LTE y 5G. En este último caso, existen diferentes tipos de celdas: las clásicas macroceldas urbanas, normalmente

ubicadas en tejados o ubicaciones elevadas; pero también las nuevas celdas milimétricas (mmWave), que se ubican en el mobiliario urbano, ya que su huella de cobertura es limitada. Además, hay usuarios que demandan los tres casos de uso (UCs) principales: eMBB (por ejemplo, usuarios que realizan tareas exigentes en términos de velocidad de datos), mMTC (por ejemplo, sensores de diferentes tipos desplegados a lo largo del escenario) y URLLC (por ejemplo, vehículos conectados). Además, se ilustran una serie de posibles problemas de red que pueden producirse en el escenario, como la interferencia entre celdas, el fallo de beam o la falta de capacidad debida a una concentración o agrupación de usuarios que demandan servicios en una zona específica.

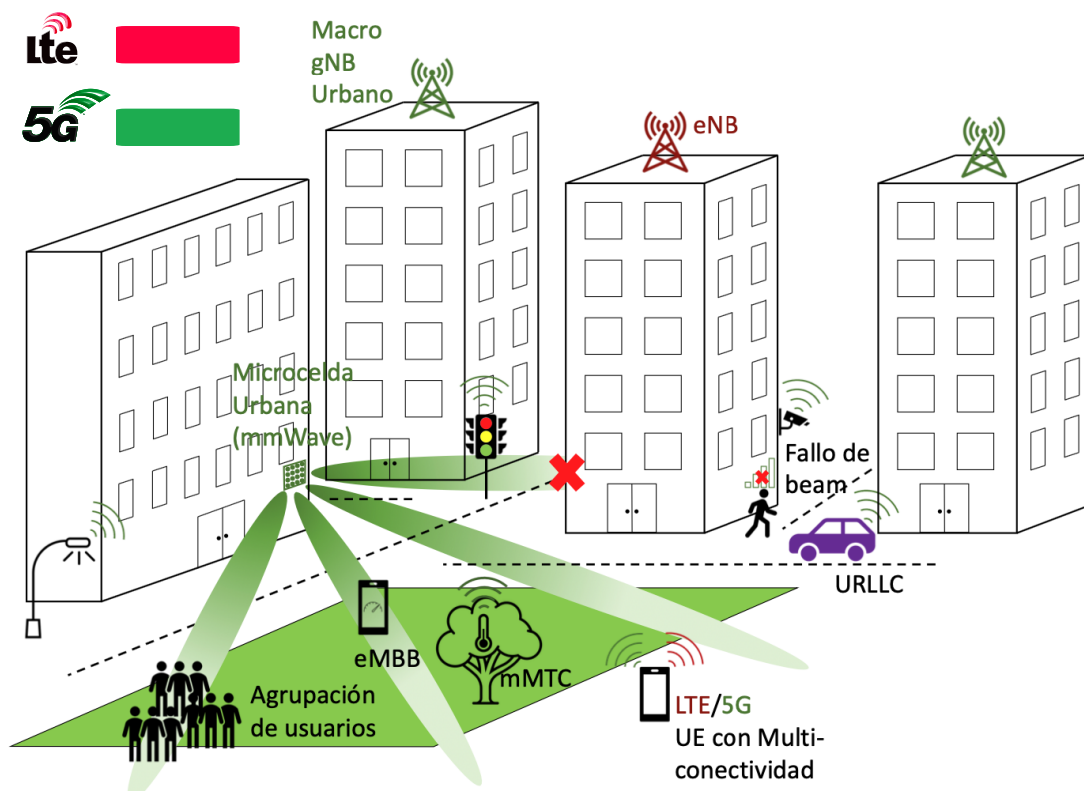


Figure A.1: Escenario 5G heterogéneo.

Como se observa en la figura, la gestión de la red es cada vez más compleja y desafiante debido al creciente número de dimensiones que hay que tener en cuenta, desde los parámetros que se pueden configurar, los nuevos elementos de red que implementan nuevas características y los nuevos servicios que se ofrecen.

En este contexto, un análisis exhaustivo de la tecnología celular 5G es el primer paso para comprender los cambios con respecto a las generaciones anteriores, así como para entender las características novedosas que se introducen en 5G (Objetivo

1). Así, esta tarea permitirá identificar las principales causas de los problemas de la RAN, así como los problemas clásicos de red que han estado presentes en las generaciones anteriores, por ejemplo, la gestión de la movilidad. Este análisis engloba el análisis bajo herramientas de simulación, y un conocimiento profundo de las especificaciones del 3GPP. El resultado de esta tarea es la identificación de los problemas candidatos que pueden presentarse en la red, aquellos para los que las soluciones actuales de gestión de red no están preparadas.

Una vez verificados bajo simulación los problemas candidatos, la propuesta de técnicas innovadoras para abordarlos constituye el segundo objetivo de esta tesis (Objetivo 2). En particular, la tecnología de *beamforming* se considera como una capa adicional de complejidad en la gestión de la movilidad, por lo que los procedimientos de gestión de *beamforming* se convierten en objeto de estudio. Además, dado el nuevo requisito exigente de la red celular en términos de UCs, las métricas del lado de la red no son suficientes para garantizar la calidad del servicio. A continuación, se evalúa la explotación de las métricas del lado del usuario (Objetivo 2.1) y de la información de localización (Objetivo 2.2) para la gestión de la red.

El análisis del rendimiento de las técnicas propuestas en despliegues reales es también un objetivo clave de esta tesis (Objetivo 3), incurriendo en la complejidad de trabajar con equipos reales, pero aportando a su vez un valor añadido a los resultados obtenidos.

Finalmente, la integración de los objetivos anteriores en un marco de gestión de red pretende proporcionar una solución probada y lista para usar a los retos de gestión de red que nacen de la introducción de la tecnología 5G (Objetivo 4).

Por tanto, los objetivos principales de la tesis se pueden resumir en los siguientes:

- **Objetivo 1:** Explorar y analizar en profundidad los aspectos novedosos de la tecnología 5G, centrándose en la RAN y los servicios que se prestan sobre la red celular. Este objetivo allana el camino hacia la identificación de los principales problemas de red, que se evalúan de forma preliminar.
- **Objetivo 2:** Proponer técnicas innovadoras para abordar las nuevas características y los problemas de red identificados en 5G, con especial atención a la tecnología de *beamforming*. Debido a la mayor complejidad de la red, se considera el uso de dos fuentes adicionales de información:

- **Objetivo 2.1:** Utilizar las métricas del lado del usuario, que proporcionan una perspectiva más rica del rendimiento real que los usuarios están experimentando. Esto permitirá identificar los principales factores que afectan a la calidad de servicio del servicio.
- **Objetivo 2.2:** Beneficiarse de la integración de la información de localización relativa a la gestión de la red. Esto proporcionará una visión más precisa de la red, permitiendo la identificación de áreas candidatas donde pueden producirse problemas y ayudando a los procedimientos de gestión de la movilidad, especialmente en lo que respecta a *beamforming*.
- **Objetivo 3:** Analizar el rendimiento de las técnicas propuestas así como la implementación de *beamforming* sobre infraestructuras reales.
- **Objetivo 4:** Desarrollar un marco de gestión que integre las técnicas propuestas, incluyendo las métricas del lado del usuario y la información de localización para la gestión de la red.

No obstante, existe un objetivo transversal que ha sido parte del trabajo durante el desarrollo de esta tesis: el despliegue de infraestructura real. Durante la tesis, se ha liderado el proyecto de despliegue de equipamiento real, no sólo considerando la parte técnica, sino también la coordinación de las diferentes entidades en la UMA, las decisiones sobre la ubicación de los emplazamientos, y la continua interacción con el operador de red móvil y el fabricante de los equipos. Este equipamiento ha sido utilizado para el desarrollo de la tesis, así como para otras actividades de investigación, desde su utilización en proyectos europeos, hasta el uso por parte de los más de 30 investigadores pertenecientes al grupo *MOBILENET*.

## A.4 Descripción del trabajo realizado

### A.4.1 Análisis e Identificación de Potenciales Problemas en 5G

Se ha realizado un análisis inicial del estado actual de la tecnología 5G, los aspectos relacionados con la estandarización y la identificación de los potenciales problemas.

Dada la naturaleza móvil de los usuarios y el entorno cambiante, las comunicaciones inalámbricas se vuelven más susceptibles a los fallos, especialmente en 5G, donde se incluyen tecnologías novedosas.

Algunas tecnologías introducidas en 5G para alcanzar un mejor rendimiento de la red, también tienen algunas desventajas. En cuanto a las señales milimétricas (mmWave), proporcionan velocidades de datos más altas, latencias más bajas y más capacidad, ya que los canales son mayores en esas bandas. Sin embargo, es importante superar sus elevadas pérdidas de trayecto y su susceptibilidad a los obstáculos o a la propagación de exterior a interior. Para ello, las técnicas de formación de haces intentan minimizar esos efectos dirigiendo las señales hacia direcciones predefinidas para mejorar la intensidad de la señal. Sin embargo, los esquemas de *beamforming* requieren el intercambio de señalización entre el gNB y el UE para estimar correctamente la calidad del canal y mantener el enlace incluso cuando los usuarios están en movimiento. Para llevar a cabo el *beamforming*, se necesitan las técnicas de múltiples antenas (MIMO). Esto significa que cada transmisor debe pausar la transmisión cuando el otro está transmitiendo señales piloto para estimar correctamente el canal. En este sentido, el funcionamiento de TDD permite la transmisión continua de información en ambas direcciones utilizando el mismo canal, por lo que se puede asumir la reciprocidad entre el enlace descendente DL y el ascendente UL, y se reduce la sobrecarga de señalización. Aunque pueda parecer una solución ideal, el uso de TDD provoca interferencias entre gNBs cercanos si sus patrones (es decir, los periodos temporales utilizados para DL y UL) no están sincronizados. Por lo tanto, conseguir estas capacidades superiores no siempre es sencillo y hay que solventar algunos inconvenientes.

Se han identificado varios problemas de 3 categorías: movilidad, cobertura e interferencia. Dichos problemas han sido probados bajo simulador, verificando su ocurrencia.

## A.4.2 Evaluación de Técnicas basadas en Beamforming sobre Despliegue Real

### A.4.2.1 Red 5G SA en la UMA

Esta parte se centra en la tecnología de *beamforming* introducida en 5G [64]. Aunque la principal motivación para utilizar *beamforming* es alcanzar mayores distancias y una mejor calidad de la señal en general, hay algunos inconvenientes que deben abordarse, por ejemplo, el cambio de *beam* [56, 71]. Además, el *beamforming* también ofrece algunas oportunidades en cuanto a la localización o el movimiento de los usuarios, que son abordados en el presente trabajo. Se han llevado a cabo experimentos utilizando la infraestructura descrita (véase la sección 4.1), y un módulo Simcom SIM8380G conectado a un ordenador portátil Lenovo L390 con Ubuntu 22.04 actuando como UE.

Por un lado, se estudia el funcionamiento del cambio de beam, mediante la recolección de medidas desde el UE para su posterior análisis. A partir de ahí, se obtienen estadísticas como el tiempo medio en un *beam*, la diferencia de calidad radio al realizar el cambio, o el resto de *beams* disponibles.

Por otro lado, se propone un sistema de localización basado en *beamforming* que permite estimar la posición de un UE dadas las métricas radio y el identificador del *beam* (*Beam ID*) al que está conectado.

Por último, se propone la definición de nuevos *KPIs* relacionados con el *beamforming* que proporcionan a la red un conocimiento generalizado sobre el movimiento que realizan los usuarios conectados.

### A.4.2.2 Red 5G mmWave en la AAU

Esta sección contiene el análisis realizado sobre las medidas experimentales. Las mediciones recopiladas están disponibles en [15]. En primer lugar, se explora la correlación entre las métricas recogidas, incluyendo radio, localización y rendimiento. Esta evaluación inicial mostró cierta relación entre la latitud (es decir, la posición en el eje y), la RSRP y el *Beam ID*. En cambio, dada la ruta seguida por el AMR, es de esperar que la longitud (es decir, la posición en el eje x) no esté relacionada, ya que el movimiento se realiza en el eje y, salvo para evitar algún obstáculo (véase la Fig. 4.13).

Se ha obtenido el número de cambios de *beams* a partir de las medidas recogidas por el UE, a partir del *Beam ID* reportador como servidor. A continuación, se han calculado las estadísticas de conmutación de haces, tiempo transcurrido en el *beam*, los casos de ping-pong y las diferencias de las métricas de radio antes y después de la conmutación de haces.

Por último, se ha propuesto un criterio diferente, basado en dicha información de localización, en relación a las condiciones que deben darse para que se inicie el proceso de cambio de *beam*.

### **A.4.3 Marco de gestión de red para la integración de métricas de usuario e información de localización**

#### **A.4.3.1 Gestión de red inteligente con conocimiento de localización**

Se propone un sistema que implementa un conjunto de capacidades que implican el procesamiento en tiempo real de mediciones y eventos de red, la identificación de la ubicación de los usuarios y la explotación de la información de ubicación para ofrecer una predicción inteligente de la cobertura de red y la detección de fallos.

Estas funcionalidades abren nuevas oportunidades para que el MNO mejore la gestión de la red. Su aplicabilidad no se limita a las métricas de calidad de radio, sino que podría extenderse a las métricas de calidad de servicio, que son cruciales para que el operador preste un buen servicio a sus clientes.

#### **A.4.3.2 Gestión de red totalmente automática a partir de datos de usuario mediante *crowdsourcing***

En esta sección se analizan las fuentes de información, detallando sus principales ventajas e inconvenientes y cómo podrían complementarse para encajar en el esquema ZSM. En este sentido, la QoS se define como la calidad objetiva, medida a través de diferentes métricas, por ejemplo, el ratio de pérdida de paquetes o el retardo del servicio. En cambio, la QoE es la calidad subjetiva percibida por los usuarios, obtenida normalmente a través de formularios en un entorno de laboratorio, y tiene en cuenta las expectativas y el contexto del usuario. La QoE suele estar relacionada con la aplicación utilizada, por ejemplo, los fotogramas congelados en streaming de vídeo, se refiere al agrado o molestia del usuario, y por

definición se ve muy afectada por la QoS. La QoS comprende el rendimiento de la red entre dispositivos finales, pero el alcance de la QoE es más amplio, ya que incluye la percepción del usuario, según la ITU [83].

Se propone un framework que integra las métricas del lado de usuario y de la red. Para el uso de las métricas del lado de usuario, se proponen una serie de técnicas de procesamiento y aplicaciones de utilidad de cara a la gestión de la red. Por último, se describen los principales retos que quedan abiertos para su implementación por parte de los MNOs.

## A.5 Conclusiones

A continuación se presentan las contribuciones relacionadas con cada uno de los objetivos que han sido definidos en esta tesis:

- **Obj. 1: Explorar las nuevas características de la RAN en 5G**
  - En primer lugar, se evalúa el estado actual del desarrollo de 5G con el fin de identificar cuáles son las nuevas características que pueden conducir a una situación problemática.
  - Se han revisado los procedimientos OAM clásicos de la red desde el punto de vista de la gestión de fallos, así como las actualizaciones del 3GPP respecto a la versión anterior de las especificaciones.
  - Tres problemas han sido validados bajo simulación, demostrando la relevancia del conocimiento de la localización y la velocidad del usuario para la gestión de dichos fallos. Los problemas identificados han sido la interrupción del servicio en mmWave, la configuración de *beamforming* y la interferencia entre enlaces cruzados TDD. Dichos problemas establecen la base para el desarrollo del resto de la tesis.
  - Se han identificado los parámetros de configuración relacionados con la gestión de la movilidad, especialmente aquellos que dependen de la implementación del fabricante. En este sentido, el *beamforming* ha introducido nuevos parámetros, que se prevén críticos para la gestión de la red.
- **Obj. 2: Proporcionar técnicas innovadoras para abordar estas características y los problemas de red introducidos en 5G**

- Se han definido nuevos KPIs aprovechando la información obtenida de los contadores relacionados con el *beamforming*. Estos KPIs proporcionan información útil para la gestión de la red, así como desde una perspectiva de detección de fallos.
  - Se ha introducido una técnica de localización basada en ML, sin costes en términos de sobrecarga y consumo de energía. Aunque la precisión no es comparable a la de GNSS, es un método interesante para los casos en los que GNSS no está disponible, ya sea desde el lado de la red o en escenarios interiores desde el UE.
  - Se ha propuesto un conjunto de condiciones para enriquecer los criterios de inicio del proceso de cambio de *beam* en mmWave. El objetivo de esta técnica es optimizar la calidad radio media y reducir el número de cambios de *beams* y de ping-pong.
  - Se ha propuesto la idea de reducir los recursos de CSI-RS cuando un usuario está estacionario. Esto se ha basado en los resultados de mmWave, de modo que la información de ubicación podría ayudar a decidir cuántos recursos se asignan a CSI-RS.
  - Los resultados de las campañas de medida realizadas en el escenario industrial sugieren la necesidad de configurar específicamente los parámetros de *beamforming* en función del escenario, especialmente en mmWave.
  - A partir del análisis realizado sobre datos reales de usuarios comerciales, se han propuesto una serie de pasos a seguir para el procesado de Next-Generation Crowdsourcing Metrics (gCMs), así como posibles aplicaciones orientadas hacia ZSM.
- **Obj. 3: Analizar el rendimiento de la funcionalidad de *beamforming* y las soluciones propuestas en despliegues reales**
- El potencial de 5G se ha puesto de manifiesto mediante las pruebas realizadas en la infraestructura basada en equipamiento comercial desplegada en el campus de la UMA.
  - El rendimiento de 5G mmWave también se ha evaluado en un escenario real en el campus de la AAU. Se ha estudiado el *beamforming* en términos de calidad de radio y reducción del número de cambios de *beams*, en un

escenario industrial realista en el que un usuario está en movimiento. Esto es relevante para los sistemas críticos dentro del caso de uso industrial, ya que son sensibles a la latencia o a las interrupciones.

- Las medidas realizadas en 5G SA y en mmWave se han puesto a disposición de la comunidad investigadora mediante la publicación de los juegos de datos recopilados.
  - En cuanto a la integración en un marco de gestión, se ha analizado el comportamiento de los diferentes componentes que trabajan juntos en una infraestructura virtualizada, evaluando la viabilidad del enfoque incluso cuando la plataforma de algoritmos de gestión y el escenario físico se encuentran en diferentes países. Las funcionalidades probadas han mostrado resultados prometedores en cuanto al aprovechamiento de la información de localización en un escenario de interiores.
  - Se ha comparado la gestión clásica de la red con el marco de gestión presentado que incorpora gCMs. Para el análisis se han utilizado gCM-Ms y gCM-Ss reales. Se han revisado y evaluado las diferentes aplicaciones de este tipo de datos, incluyendo sus ventajas e inconvenientes.
- **Obj. 4: Desarrollar un marco de gestión integrando las métricas del lado del usuario y la localización.**
    - Se ha generado un conocimiento sobre cómo se pueden optimizar los procedimientos de *beamforming* a partir del trabajo realizado en mmWave, donde la información de localización desempeña un papel clave para este objetivo.
    - Se ha llevado a cabo el diseño y la implementación de una infraestructura de gestión de red consciente de la localización en un entorno mundo real, donde las funcionalidades de gestión de red aprovechan la información de localización recibida en tiempo real. Se ha demostrado que la información de localización es crucial para la gestión de la red, incluso en un escenario Sub-6 GHz en interiores.
    - Se ha revisado el uso de gCMs hacia el enfoque futuro de ZSM, y se ha propuesto un enfoque novedoso para el procesamiento de los datos y aplicación en la gestión de redes.

Adicionalmente, se ha cumplido con éxito el objetivo transversal del despliegue

de infraestructura real. En este sentido, la configuración de los equipos para su integración en la infraestructura de la UMA, el apoyo al equipo de configuración del fabricante, el acceso remoto, el apoyo a la actualización de los equipos, la instalación de servidores para ofrecer servicios locales, y la asistencia al resto de investigadores que han querido hacer uso de la infraestructura, han sido algunas de las tareas realizadas.

## A.6 Actividades de investigación

### A.6.1 Resumen de contribuciones

#### Artículos de revista

- [1] **A. Tarrías**, S. Fortes and R. Barco, “Failure Management in 5G RAN: Challenges and Open Research Lines”, in *IEEE Network*, vol. 37, no. 5, pp. 215-222, Sept. 2023.
- [2] **A. Tarrías**, E. Baena, S. Fortes and R. Barco, “Leveraging 5G SA for R&D: Capabilities and Beam-Based Empirical Analysis”, in *IEEE Open Journal of the Communications Society*, vol. 5, pp. 5608-5618, 2024.
- [3] **A. Tarrías**, I.Hadj-Kacem, G. Bernini, T.E. Kennouche, H.Q. Luo-Chen, M. D. Angelis, A. Margaris, E. Baena, E.J. Khatib, S.B. Jemaa, S. Bartoletti, S. Fortes and R. Barco, “Location-Aware Smart Network Management in Advanced Networks: Design and Applied Proof of Concept”, in *IEEE Network*, accepted Oct. 2024.
- [4] **A. Tarrías** , A. A. Moreno, F. J. Pareja, E. Baena, S.Fortes, “Towards Zero-Touch Cellular Networks via Next-Generation Crowdsourcing”, *TechRxiv*. March 14, 2023. - *Under Review*
- [5] **A. Tarrías**, S. B. Damsgaard, M. López, T. B. Sørensen, P. E. Mogensen, S. Fortes, R. Barco, “Beam Switching in mmWave 5G: Evaluation in a Realistic Industrial Scenario”, *TechRxiv*, 2024. - *Under Review*

*Contribuciones adicionales:*

- [6] C. S. Álvarez-Merino, E. J. Khatib, H. Q. Luo-Chen, **A. Tarrías-Muñoz** and R. B. Moreno, ”Evaluation and Comparison of 5G, WiFi, and Fusion

With Incomplete Maps for Indoor Localization,” in *IEEE Access*, vol. 12, pp. 51893-51903, 2024

## Conferencias internacionales

- [7] **Antonio Tarrías**, Sergio Fortes and Raquel Barco, “Failure management insights in 5G using ns-3 network simulation”, *INTERACT 2nd MC and 1st Technical Meetings*, 2022. Bologna, Italy.
- [8] **Antonio Tarrías**, Alejandro A. Moreno, Francisco Pareja, Eduardo Baena, Raquel Barco and Sergio Fortes. “UE Side Application Layer Metrics for QoE-Based Network Management”, *2023 EuCNC & 6G Summit - Posters*. Gothenburg, Sweden.

## Conferencias nacionales

- [9] **Tarrías, A.**; Fortes, S.; Baena, E. and Barco, R. “Análisis del efecto del número de beams sobre un escenario 5G” *XXXV Simposium Nacional de la Unión Científica Internacional de Radio (URSI)*, Málaga (Online) 2020
- [10] **Tarrías, A.**; Fortes, S.; Baena, E. and Barco, R. “Análisis de Interferencia Cross-Link sobre un escenario 5G mmWave” *XXXVI Simposium Nacional de la Unión Científica Internacional de Radio (URSI)*, Vigo (Online) 2021
- [11] **Tarrías, A.**; Baena, E.; Fortes, S. and Barco, R. “Infraestructura 5G Standalone para Investigación y Desarrollo” *XXXVII Simposium Nacional de la Unión Científica Internacional de Radio (URSI)*, Málaga, 2022

*Contribuciones adicionales:*

- [12] Álvarez-Merino, C.S.; **Tarrías, A.**; Luo Chen, H.Q. ; Jatib-Khatib, E. and Barco, R. “Posicionamiento 5G con mapas radio incompletos” *XXXVIII Simposium Nacional de la Unión Científica Internacional de Radio (URSI)*, Cáceres, 2023
- [13] Jatib-Khatib, E.; Segura-Ramos, D.; **Tarrías, A.** and Barco, R. “Estudio del ataque de cadena de suministro sobre XZ utils y sus consecuencias en telecomunicaciones” *XXXIV Simposium Nacional de la Unión Científica Internacional de Radio (URSI)*, Cuenca, 2024

## Conjuntos de datos

- [14] **Antonio Tarrías**, Eduardo Baena, Sergio Fortes, Raquel Barco, “UE and Network Side Metrics Dataset in Private 5G SA Deployment with Localization and Beamforming Information”, June 17, 2024, *IEEE Dataport*, doi: <https://dx.doi.org/10.21227/302r-w050>.
- [15] **Antonio Tarrías**, Sebastian B. Damsgaard, Melisa López, Troels B. Sørensen, Preben E. Mogensen, Sergio Fortes, Raquel Barco, “5G mmWave Dataset with Beamforming in a Realistic Industrial Scenario”, September 12, 2024, *IEEE Dataport*, doi: <https://dx.doi.org/10.21227/r02m-zx61>.

### A.6.2 Exposiciones y demostraciones

Las aportaciones del trabajo también se han mostrado en forma de exposiciones en conferencias y eventos tecnológicos. Estas exposiciones han permitido el intercambio de enfoques innovadores y resultados de investigación de esta tesis, facilitando un valioso intercambio de conocimientos y experiencias con la comunidad académica y profesional.

Así, las distintas aportaciones del trabajo se han presentado en los siguientes eventos:

- Mobile Week Málaga 2021, organizado por el Palacio de Ferias y Congresos de Málaga (FYCMA) en Málaga (España), Diciembre 2021.
- Demostración en el expositor del proyecto H2020 LOCUS en el congreso EuCNC & 6G Summit 2022, Junio 2022, en Grenoble (Francia).
- Presentación ante la Comisión Europea (formato virtual) durante la justificación de los resultados del proyecto H2020 LOCUS, Enero 2023.

### A.6.3 Related projects

Esta tesis ha sido financiada por el Ministerio de Ciencia, Innovación y Universidades a través del programa Ayudas para la Formación de Profesorado Universitario. FPU20/02863.

El trabajo desarrollado en esta tesis ha contribuido a los siguientes proyectos, que también han financiado parcialmente esta tesis:

- **LOCUS:** LOCalization and analytics on-demand embedded in the 5G ecosystem, for Ubiquitous vertical applicationS. Grant agreement No. 871249, cuyos fondos provienen del programa de investigación e innovación Horizonte 2020 de la Comisión Europea.
- **MUSE:** MUSE - Massive User Experience Assessment and Prediction for Mobile Networks. Identificador UMA-CEIATECH-15, cuyos fondos provienen de la Junta de Andalucía (Campus de Excelencia Internacional Andalucía TECH) y el European Regional Development Fund (ERDF).
- **MAORI:** Massive AI for the OpenRadIo b5G/6G network. Project number TSI-063000-2021-75, con fondos del Ministerio de Asuntos Económicos y Transformación Digital and European Union - NextGenerationEU en el marco de “Recuperación, Transformación, y Resiliencia”.

#### A.6.4 Estancias de Investigación

Esta tesis ha supuesto una estancia como investigador visitante en la Sección de Redes de Comunicación Inalámbricas (WCN), en el departamento de Sistemas Electrónicos de la Universidad de Aalborg (AAU), entre febrero y junio de 2023. Esta estancia fue supervisada por el profesor asociado Troels Bundgaard Sørensen y el profesor Preben Mogensen. Preben Mogensen es Bell Labs Fellow en Nokia y también ocupa un puesto de profesor a tiempo parcial en la Universidad de Aalborg (Dinamarca).



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# Part V

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