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TESIS DOCTORAL

Context-aware novel techniques for advanced cellular network management

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Por la presente, el **Dr. D. Sergio Fortes Rodríguez** y la **Dra. Dª. Raquel Barco Moreno**, profesores del *Departamento de Ingeniería de Comunicaciones* de la Universidad de Málaga,

CERTIFICAN:

Que **D. Eduardo Baena Martínez**, Ingeniero de Telecomunicación, 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:

"Context-aware novel techniques for advanced cellular network management"

En dicho trabajo se han propuesto aportaciones originales para la gestión de problemas de degradación del servicio en redes móviles debido al contexto. En particular, se han propuesto métodos para el desarrollo de la conciencia social y de localización, para la monitorización centrada en usuario y finalmente para el aprovisionamiento optimizado en bandas no licenciadas. Los resultados expuestos han dado lugar a publicaciones en revistas y aportaciones a congresos.

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A la conciencia,
en cada una de sus expresiones

*"If you have built castles in the air, your work need not be lost;
that is where they should be. Now put the foundations under them"*

Henry David Thoreau in "Walden"

Acknowledgments

...or the section of prosaic unfairness

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Music and Art for allowing us to fly high

...and very grateful to all people who inspire: from the present, from the past and from the future.

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Abstract

The continuous increase in traffic on mobile networks due to the massive adoption of devices that require broadband connectivity has resulted in a vast and complex infrastructure, the management of which is a significant challenge for operators. Although the arrival of new generations of cellular communications standards such as 4G or 5G incorporates a number of innovations to tackle this task, such as the proposal of automatic management or Self-Organized Networks (SON), today's operation and management systems still lack sufficient flexibility to maximize their efficiency to the requested quality level.

On the one hand, there are contextual situations where, from a network point of view, a given area is well covered, but users of specific applications may experience an unpleasant service experience. These resulting Quality of Experience (QoE), which network operators are well aware of its importance, has not been possible to incorporate so far at the management level in an agile manner. On the other hand, the very dynamic nature of human users means that traffic can fluctuate very suddenly in one place, such as during a traffic jam or a social event. In this case, the networks are not able to anticipate or manage the available resources to them correctly, and on many occasions, failures occur, or inadequate quality is offered. These undesired effects are partly due to the lack of a system that incorporates localization natively.

Besides, there are locations, especially indoors, that are currently not cost-effective to provide coverage despite the concentrations of people they host. Such a situation arises because it would require a very high cost and extensive deployment to maintain, and its use would be intermittent, wasting resources.

At this point, this thesis proposes to address some of the weaknesses mentioned earlier and gaps in recent cellular network deployments. Thus, three new context-aware mechanisms are presented as enablers of a new, more intelligent generation in network management and operation. Driven by the rapid development of Artificial Intelligence (AI), the advance of virtualization technologies extended to radio signal processing and the increasing ease of embedding localization in the collected data

the inclusion of context-awareness in the autonomous management of the cellular network becomes feasible.

Firstly, based on the current state-of-the-art automatic management systems, localization awareness is developed to enable the optimal generation of synthetic network images to characterize operating states. Taking advantage of deep learning classification algorithms, a framework is proposed to improve the performance of autonomous cellular network management tasks. Subsequently, by including open sources, a method for anticipating the impact of social events on network metrics is proposed.

Second, a framework for systematically collecting user traces without privacy invasion using virtualized probes is presented. This method enables QoE (User-centric) awareness in the network by incorporating critical objective indicators in crowded scenarios.

Third, an approach is developed where the use of unlicensed bands increases capacity in very dense indoor environments where WiFi is currently deployed. On the one hand, a service evaluation that would be experienced by cellular users in situations of coexistence with the available channel access mechanisms is carried out. On the other hand, an optimization of the in-band signaling is proposed in order to improve this quality, avoiding behaviors detrimental to WiFi.

For effective validation and accurate feasibility assessment, all these approaches have been developed either by experimental means or multi-layer realistic simulations.

Resumen

El continuo aumento del tráfico en las redes móviles, debido a la adopción masiva de dispositivos que requieren conectividad de banda ancha, ha dado lugar a una infraestructura amplia y compleja, cuya gestión supone un importante reto para los operadores. Aunque la llegada de las nuevas generaciones (4G o 5G) de estándares de comunicaciones celulares incorpora una serie de innovaciones para abordar esta tarea, como la propuesta de gestión automática o las redes autogestionadas (SON); los sistemas de operación y gestión actuales siguen careciendo de la flexibilidad suficiente para maximizar su eficiencia hasta el nivel de calidad requerido.

Por un lado, hay situaciones contextuales en las que, desde el punto de vista de la red, una zona determinada está bien cubierta, pero los usuarios de aplicaciones específicas pueden experimentar una experiencia de servicio no satisfactoria. Esta calidad de experiencia (QoE) resultante, de cuya importancia los operadores de red son muy conscientes, no ha sido posible incorporarla hasta ahora a nivel de gestión.

Por otra parte, la propia naturaleza dinámica social de los usuarios hace que el tráfico pueda fluctuar muy repentinamente en un lugar, como por ejemplo durante un atasco o un evento multitudinario. En este caso, las redes celulares no son capaces de anticipar o gestionar correctamente los recursos disponibles para ellos, y en muchas ocasiones se producen fallos o se ofrece una calidad inadecuada. Estos efectos no deseados se deben en parte a la falta de un sistema que incorpore la localización de forma nativa. Además, existen emplazamientos, especialmente en interiores, que actualmente no son rentables para dar cobertura a pesar de las concentraciones de personas que albergan. Esta situación se produce porque su mantenimiento requeriría un coste muy elevado y un gran despliegue, y su uso sería intermitente, con el consiguiente desperdicio de recursos.

Ante este escenario, la presente tesis propone subsanar algunas de las debilidades mencionadas anteriormente y las carencias de los recientes despliegues de redes celulares. De este modo, se presentan tres nuevos mecanismos como habilitadores de una nueva generación más inteligente en la gestión y operación de redes con conciencia contextual.

La inclusión de dicha conciencia en la gestión autónoma de la red celular sería factible dado el rápido desarrollo de la Inteligencia Artificial (IA), el avance de las tecnologías de virtualización extendidas al procesamiento de señales de radio y la creciente facilidad para incorporar la localización en los datos recogidos.

En primer lugar, partiendo del estado del arte actual de los sistemas de gestión automática, mediante la inclusión de fuentes abiertas, se propone un método para anticipar el impacto de los eventos sociales en las métricas de la red. Posteriormente, aprovechando los algoritmos de clasificación de aprendizaje profundo, se propone un marco para mejorar el rendimiento de las tareas de gestión autónoma de la red celular. De este modo, se desarrolla una conciencia de localización que permite la generación óptima de imágenes sintéticas de la red caracterizando diversos estados de funcionamiento.

En segundo lugar, se presenta un marco de trabajo para recopilar sistemáticamente trazas de usuario, sin invadir su privacidad, utilizando sondas virtualizadas. Este método permite la monitorización avanzada de la QoE (centrada en el usuario) en la red mediante la incorporación de indicadores objetivos críticos en escenarios de aglomeraciones.

En tercer lugar, se desarrolla un enfoque para el aprovisionamiento de bandas no licenciadas aumentando la capacidad en entornos interiores muy densos en los que actualmente se despliega WiFi. Por un lado, se realiza una evaluación del servicio que experimentarían los usuarios celulares en situaciones de coexistencia con los mecanismos de acceso al canal disponibles. Por otro lado, se propone una optimización de la señalización en banda para mejorar esta calidad, evitando comportamientos perjudiciales para el WiFi.

Para una validación eficaz y una evaluación precisa de su viabilidad, todos estos mecanismos se han probado por medios experimentales o por simulaciones realistas que reflejan las interacciones multicapa propias del funcionamiento de las redes comerciales.

Acronyms

3GPP	3rd Generation Partnership Project
5G	Fifth Generation of Mobile Networks
AFC	Automatic Frequency Control
AI	Artificial Inteligence
AMF	Account Management Function
ANOVA	Analysis of the Variance
API	Application Program Interface
AP	Access Point
BBU	Base Band Unit
BS	Base station
BW	Bandwidth
CAPEX	CApital EXpenditures
CBR	Call Blocking Ratio
CBRS	Citizens Broadband Radio Service
CCA	Clear Channel Assessment
CDR	Call Detail Record
CDRS	Compensated DRS
CDF	Cumulative Distribution Function
CID	Cell ID

CM	Configuration Management
COTS	Commercial Off-The-Shelf
CWS	Contention Window Size
C-RAN	Cloud Radio Access Network
CSMA/CA	Carrier Sense Multiple Access Collision Avoidance
CQI	Channel Quality Indicator
DCF	Distributed Coordinated Function
DL	Deep Learning
DNS	Domain Name System
DRS	Discovery Reference Signal
DT	Drive Test
E2E	End-to-end
eLAA	enhanced Licensed Assisted Access
eMBB	enhanced Mobile BroadBand
eNodeB	Evolved Node B
EPC	Evolved Packet Core
epdf	Empirical probability density function
EPS	Evolved Packet System
FCC	Federal Communications Commission
FM	Fault Management
FTP	File Transfer Protocol
gNodeB	New Radio Node B
GPP	General Processing Platform
GSM	Global System for Mobile Communications
IoT	Internet-of-Things

IP	Internet Protocol
ITU-T	International Telecommunication Union-Telecommunication
JSON	JavaScript Object Notation
KPI	Key Performance Indicator
KQI	Key Quality Indicator
LAA	Licensed Assisted Access
LBT	Listen Before Talk
LMF	Location Management Function
LTE	Long Term Evolution
LTE-A	Long Term Evolution - Advanced
MAC	Media Access Control
MBB	Mobile BroadBand
MCOT	Maximum Channel Occupacy Time
MDT	Minimization of Drive Tests
ML	Machine Learning
MME	Mobility Management Entity
MNO	Mobile Network Operator
NAS	Nextwork Access Stratum
NE	Network Element
NF	Network Function
NFV	Network Virtualization Function
NG-SON	Next Generation SON
NMS	Network management System
NR	New Radio
NR-U	New Radio Unlicensed

NWDAF	Network Data Analytics Function
OAM	Operations, Administration and Management
OpenRAN	Open Radio Access Networks
OPEX	OPerational EXpenditures
OSI	Open Systems Interconnection
OSS	Operational Support System
PCI	Physical Cell ID
PCF	Policy Control Function
PDCP	Packect Data Convergence Protocol
pdf	Probability density function
PDSCH	Physical Downlink Shared Channel
PHY	Physical Radio Layer
PM	Performance Management
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RB	Radio Bearer
RB	Resource Block
RLC	Radio Link Control
RF	Radio Frequency
RRC	Radio Resource Control
RRH	Radio Remote Head
RRM	Radio Resource Management
RSRP	Reference Signal Receive Power

RSSI	Received Signal Strength Indication
SAS	Switched Access Services
SDN	Software Defined Networks
SDR	Software Defined Radio
SINR	Signal-to-interference-plus-noise ratio
SLA	Service Level Agreement
SMF	Session Management Function
SON	Self Organizing Networks
TR	Technical Recommendation
TS	Technical Specification
TSN	Time Sensitive Networks
UAV	Unmanned Aerial Vehicle
UE	User Equipment
UL	Uplink
UPF	User Plane Function
URLLC	Ultra Reliable Low Latency Communications
VR	Virtual Reality
vUE	virtual UE
vRAN	virtual Radio Access Network
WAN	Wide Area Network
WiFi	Wireless Fidelity
WiGig	wireless standard developed by the Wireless Gigabit Alliance

Part I

Background

Chapter 1

Introduction

Content

This chapter clarifies the motivation and purpose of this thesis, presents its preliminaries and objectives and describes the organization of this document.

1.1 Motivation

The upsurge in the digitalization of modern societies, which has been particularly driven by the COVID-19 pandemic, has accelerated the proliferation of devices capable of connecting via cellular networks. It is thus not uncommon today to find an onboard computer in a car, virtual reality glasses, or a tiny sensor with mobile connectivity. As a result, the range of services on offer has been increasing and diversifying, being very heterogeneous in its requirements to the network. According to recent studies [1], all this acceleration in the mass adoption trend means that traffic demand by 2026 from cellular network users is expected to reach 1.5M petabytes, equivalent to 214M hours of 4K video.

In this environment, the management and operation of the cellular network is becoming increasingly complex as the number of devices and traffic demand on the network increases.

As a consequence, Mobile Network Operators (MNOs) face an increasing challenge to contain capital expenditure (CAPEX) while keeping operating expenditure (OPEX) to a minimum. Despite the fact that 4G or Long Term Evolution (LTE) technology [2] contributed to simplifying the management system architecture, current deployments are still rigidly defined and have static functionalities. In this respect, many cellular network planning and management tasks are still today mainly manual and require time-consuming support structures.

With all these drawbacks in mind, the concept of self-organizing networks (SON) was introduced based on the requirements defined by MNOs in the Next Generation Mobile Networks Alliance (NGMN) [3]. The objective of this innovation was to provide cellular networks with the intelligence and adaptability to enable autonomous management. In this sense, its primary goal is to increase network capacity, coverage, spectral efficiency, and resilience while reducing operation, administration, and maintenance (OAM) costs [4, 5]. This proposal has encouraged academia to propose and develop a plethora of algorithms for such SON tasks [6] as well as commercial products that are offered as an add-on for the Radio Access Network (RAN). However, despite its rapid evolution to the 5G standard as Next Generation SON (NG-SON), [7], there are still many aspects in its implementation that cause serious drawbacks, and that can be clearly improved. Among these aspects, it is worth highlighting the following:

- Cellular network management systems primarily work based on classical network metrics such as throughput, dropped calls, or coverage level. While valid at an overall level, these indicators do not periodically monitor users' satisfaction levels. In other words, they do not consider the quality of experience (QoE) of the user of a service or application supported by mobile network connectivity [8].
- The reactive principle is what drives the traditional operation of cellular networks. As a result, there is no capacity to anticipate possible fluctuations in demand or potential problems associated with an incident that may occur in the future, even when this demand corresponds to contextual situations that can be predicted based on digitally accessible information sources [9].
- In highly dynamic environments such as crowded indoor scenarios (i.e., subways, malls), it is extremely difficult to provide continuity in the quality offered to users [10].

At this point, the unsteady progress of Information Technologies (IT) has made available to the market a series of tools that can act as SON enhancers covering the points mentioned above.

Firstly, it is worth highlighting the current accessibility and ease of use of Artificial Intelligence (AI) [11] with a plethora of libraries, algorithms, databases, APIs, etc available. Given the decreasing cost of storage and computational resources, together with the availability of data for training based on Machine Learning (ML) principles, AI algorithms have become increasingly powerful. Techniques such as Deep Learning (DL) [12, 13, 14, 15] and Generative Adversarial Networks [16] have allowed their application in almost any field, including network management [7].

Secondly, traditional hardware equipment that perform the various network functions (switching, routing, firewalling, etc.) has transformed into software-based virtual machines that run on general-purpose machines (servers) in a process known as Network Function Virtualization (NFV). These functions can be orchestrated and managed through Software Defined Networks (SDN) [17], achieving a high degree of versatility compared to their predecessors.

Thirdly, accessing data at the user level, which has traditionally been done through measurement campaigns known as Drive Test (DT) [18], is very expensive and inefficient. These collections do not reflect the temporal evolution of the network operation (change of parameters, user mobility, environmental conditions...) even though improvements such as Minimization Drive Test (MDT)[19] have been introduced to make it more accessible. In addition, location data have so far been challenging to gather and classify by operators. Still, they can now be obtained very inexpensively and dynamically without user intervention [20, 21, 22, 23].

Taking into account the increasingly flexible and cost-effective availability of these enablers and taking advantage of the available resources, some developments can be envisaged: on the one hand, Machine Learning (ML) can be applied to anticipate possible context-derived problems that may arise given the massive availability of data using multi-factor prediction techniques and, on the other hand, automatic QoE monitoring [24] can be employed in order to optimize the performance of user applications in both licensed and unlicensed bands.

1.2 Preliminaries

This thesis was carried out at the *Mobile Network Optimization Group* (MOBILENET) of Universidad de Málaga, belonging to the TELMA Institute (GIC, TIC-102). This research team is dedicated to the improvement of current and to the design of future mobile telecommunications networks, especially by the development of novel SON techniques. The MOBILENET group originated in 2000 in a collaboration of the GIC with Nokia Networks to create a Research Center for Mobile Communications, established at the *Parque Tecnológico de Andalucía* (PTA) in Málaga, whose personnel included experienced Nokia staff, as well as more than 50 employees and lecturers from the GIC. One of the starting projects for this collaboration consisted on the development of an automatic troubleshooting tool for *radio access networks* (RANs), which established some of the basis for the incorporation of real cellular network data and engineers experience into automatic troubleshooting systems.

Since the beginning of its activity, the MOBILENET group has taken part in projects for the development of SON techniques in consortiums with national and international companies. Some of the most representative are EUREKA CELTIC project "GANDALF: Monitoring and self-tuning of RRM parameters in a multi-system network" (2005-2008) and MONOLOC (2011-2014). During the course of these projects, a system-level LTE simulator was developed and successively improved to include localization capabilities. In this background, the thesis work of Sergio Fortes [9] laid the foundations for the definition and use of contextual information in Self Healing of small cell networks. In this sense, the present thesis takes some principles and data obtained from simulations of this previous work extending the concept of context in current cellular networks.

A substantial part of the development of this thesis has been partially framed in the MONROE project [25] focused on the design, construction and operation of the first open access and flexible hardware-based platform for customised measurements and experimentation in operational Mobile Broadband (MBB) networks. Within this project, the eSON proposal (2nd OpenCall 2016 proposal) was carried out, which was based on the end-to-end capture of radio layer data at the user devices while knowing and controlling the radio network configuration parameters.

Besides, the study of unlicensed bands usage in 3GPP based technologies contained in this thesis has been proposed within the ONE5G project [26] aiming to research and deliver highly generic performance optimization schemes for the 5G New Radio, in order to achieve successful deployment and operation, including optimizations for both the network operator and the E2E user-experienced performance. Part of the work has also been integrated into the framework of the European H2020 project LOCUS [27] (LOCalization and analytics on-demand embedded in the 5G ecosystem, for Ubiquitous vertical applicationS) with special focus on localization and intelligent network management.

1.3 Challenges and objectives

This thesis proposes novel strategies for dealing with service degradation produced caused by a contextual situation from the point of view of automatic cellular network management.

More specifically, as shown in the Figure 1.1, three approaches to the problem are proposed, including several possible scenarios.

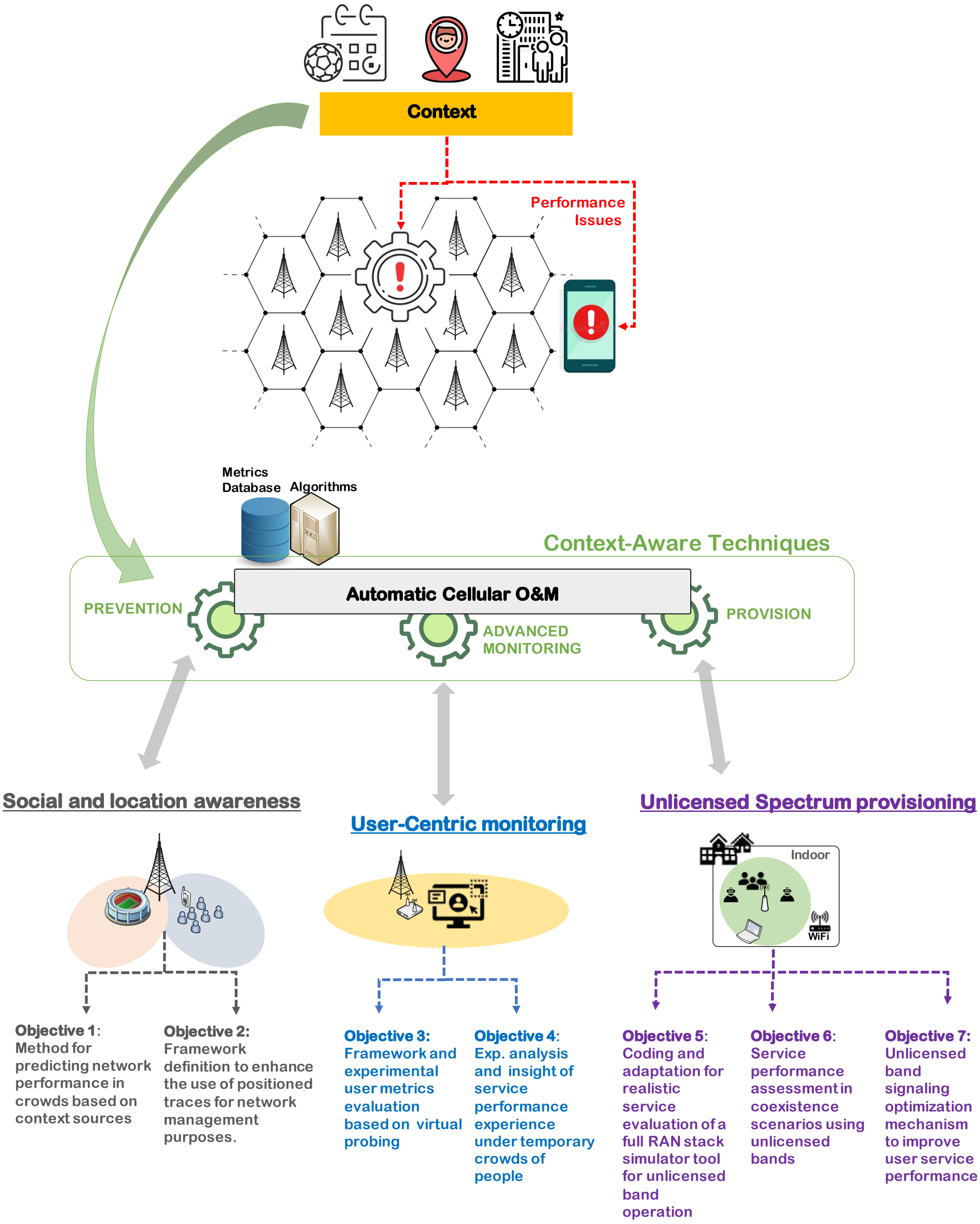

Figure 1.1: Conceptual scheme of the objectives addressed.

As a first step, there is a need to shift from mostly reactive management to a proactive operational strategy. This change has become feasible due to the maturity of Big Data processing systems and the progressive reduction of the cost of data processing and storage technologies. In this way, service degradations produced contextually can be predicted with a certain degree of reliability in situations arising from the social activity of users, such as venues or events. Additionally, automatic management systems must be able to assess the impact that such events may have on the service. (Objective 1)(Objective 2)

Another fundamental aspect to be pursued in the operation of cellular networks is to achieve a specific guarantee of the quality of experience (QoE) offered to users. Such a challenge has not been fully achieved so far, essentially for two reasons. One is the lack of objective metrics that are able to reflect such quality, and the other is the low availability of user traces that report such quality for non-intrusive reasons. The flexibility offered by the network softwarization paradigm offers a beneficial perspective for the use of probes capable of collecting such information without invading privacy. In addition, the powerful analytical tools provided by Machine Learning demonstrate promising potential in this regard. (Objective 3)(Objective 4)

Lastly, an important point to consider is that cellular network capacity has to be continuously increased due to the constant growth in traffic demand, new services introduced, and coverage expansion. Especially in indoor environments, where macro coverage is not sufficient to meet capacity needs, this is a serious drawback. In this area, the use of unlicensed bands is a promising strategy, although not without difficulties and risks, as ubiquitous WiFi technology is already deployed in these bands. Some of the challenges are: the limited knowledge of how it would affect the interoperability of coexisting systems, the lack of realistic information on the evaluation of the performance of services under different conditions, and how the sending of signaling information influences the other transmissions. (Objective 5)(Objective 6)(Objective 7)

In this way, the main objectives of the thesis can be summarized as:

Objective 1: Method for predicting network performance in crowds based on context sources. By adding to current network management systems the ability to integrate information from contextual open sources (such as online social event calendars, social networks, online databases and others), patterns of network behaviour caused by the concentration of users in an area can be established. In this way, relying on forecasting mechanisms, the network is able to prevent a possible congestion that causes a sudden degradation during the time that the concentration of people lasts.

Objective 2: Framework definition to enhance the use of positioned traces for network management purposes. The increasing availability of positioning data adds value to the information associated with the management data collected by the cellular network. However, it is necessary to adapt the current systems so that the processing of this information represents an advantage that leads to better performance.

Objective 3: Framework and experimental user metrics evaluation based on virtual probing. Another source of information that is clearly much more accessible is data about the quality of user experience. This is because, unlike systems where user devices are specific hardware, virtualization systems allow virtual terminals to be instantiated without the need to invade the privacy of the user.

Objective 4: Experimental analysis and insight of service performance experience under temporary crowds of people. The lack of perception by network management systems of the quality of service independently of network indicators is currently one of the handicaps that prevent the application of the user-centric principle. As a complement to crowd forecasting systems, the determination of the impact on QoE in this type of scenarios is proposed.

Objective 5: Coding and adaptation for realistic service evaluation of a full RAN stack simulator tool for unlicensed band operation. Since the use of unlicensed bands is subject to regulation by spectrum management agencies, there are no certified devices capable of operating in these bands. In order to enable the operation, it is necessary to have a tool that provides data as realistic as possible of what a functional deployment would be like.

Objective 6: Service performance assessment in coexistence scenarios using unlicensed bands. As with the presence of crowds, another key scenario where service degradation is more likely to occur is the indoor environment. Especially in the unlicensed band where several technologies coexist, it is crucial to establish the limits where the use of this spectrum brings advantages.

Objective 7: Unlicensed band signaling optimization mechanism to improve user service performance. Once the impact on service of coexistence in the unlicensed spectrum of cellular technologies has been determined, user-centric network operation mechanisms are required to automatically improve QoE.

1.4 Document structure

This thesis manuscript observes the same top-down approach followed by the objectives presented in the previous section. In this way, the report is divided in different parts containing multiple chapters as shown in Figure 1.2.

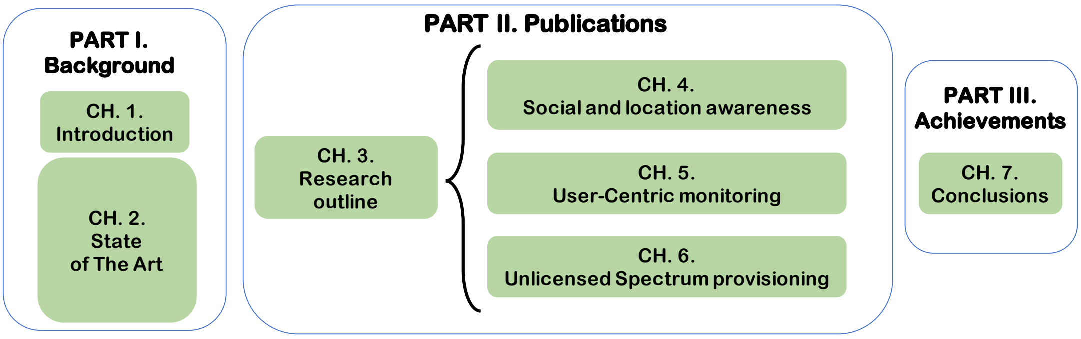

Figure 1.2: Organization of the chapters.

This report is organized in three parts, comprising a total of seven chapters. The first part is an introduction of the motivation that led to the research conducted, followed by the theoretical background necessary to understand the technical content and state of the art of the proposed techniques. The second part includes the works that have given rise to this thesis in the form of journal publications classified by their focus. The third part summarizes the conclusions and suggests future lines of research.

Part I - Background presents the preliminaries required for the proper understanding and development of the thesis. This starts with the present introductory Chapter 1 which defines the objectives to be achieved, Chapter 2 summarizes the state of the art of automatic network management, highlighting the fundamental aspects of its functioning and operation, then details the existing advances in the literature on location and social awareness with emphasis on forecasting techniques, and finally closes with an overview of the proposals for the integration of unlicensed spectrum in cellular technology and its most important characteristics.

Part II - Publications

Due to the fact of presenting this PhD dissertation in the modality of "thesis by compendium of publications", Chapter 3 presents the research outline where an integral point of view is observed where the existing challenges in the operation and management of cellular networks are mapped with the objectives stated in this thesis, clearly identifying the articles that cover each one of them. A methodological description of the steps followed is also included.

Chapter 4 develops the content of two journal publications that enable social and location awareness in the context of network management. The first one proposes a method for predicting network performance indicators at the cell level based on social event information obtained from open sources available on the Internet. The second one proposes a framework for working with location-aware traces so that different network states can be identified by means of images using a supervised Deep Learning method.

Chapter 5 directly addresses user-centric monitoring through a framework that exposes the use of virtualization and software-defined radio paradigms for obtaining on-demand user traces as well as indicators of the experienced application quality. An experimental setup is also presented where the impact on different applications is studied in a place where a social event takes place.

Chapter 6 contains the contributions made to effectively provisioning unlicensed bands in cellular technologies. In the first work, a study of quality of experience indicators in an indoor coexistence environment with a high use density is carried out and evaluated through a simulator with a multilayer implementation. The second publication studies the impact of the DRS signaling type when coexisting with WiFi and proposes optimizing its configuration based on the existing conditions.

Part III - Achievements consists of Chapter 7 which presents an overview of the results and summarizes the main conclusions and future lines of research.

Appendices: Appendix A describes the evaluation tools and testbeds used through the research. Finally, the summary of the thesis in Spanish is provided in Appendix B.

Chapter 2

State of the art

Content

This chapter summarizes the technical principles of cellular networks necessary for understanding the contributions made in this thesis.

The first section describes the main components of the current cellular network architecture common to both 4G and 5G. It also introduces the terminology of the 3rd Generation Public Private Partnership (3GPP) standardization body, outlining the innovations introduced for the virtualization of the infrastructure and for operating in unlicensed spectrum. The second section reviews the concepts related to the management and operation of cellular networks. More specifically, the self-organizing networks (SON) concept is explained, followed by those innovations that are shaping next-generation cellular networks transitioning to a fully autonomous management model. The third section provides a brief summary of the state of the art of each research areas covered in the thesis: Social and Location awareness, User-Centric monitoring and Unlicensed Spectrum provisioning

2.1 Overview of 3GPP standards

A cellular network can be defined as a set of interlinked elements capable of providing seamless wireless connectivity so that attached devices can move freely over the covered area. These devices, known as User Equipment or UE, are supplied with modems that comply with the 3GPP cellular network standard. Although they are usually associated with smartphones or tablets, technological developments have led to their extension to sensors, connected cars, robots, drones, or industrial machines.

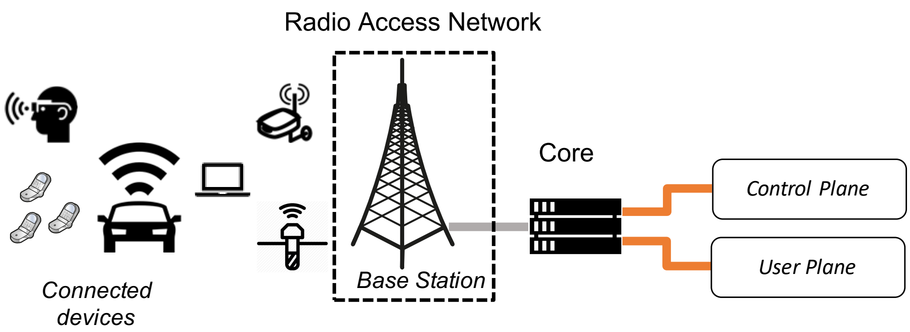

Figure 2.1: Cellular network architecture diagram

In the cellular network, there are two distinct but integrated components:

- The Radio Access Network (**RAN**) manages the RF spectrum so that users can obtain certain network service requirements. These are, in turn, translated into Quality of Experience (QoE) levels depending on the specific application that makes use of the network resources provided.

  As shown in Figure 2.1 part is mainly made up of a set of access nodes or Base Stations (BS) distributed over a given area. In the fourth generation 3GPP standard, these nodes are known as enhanced Node Bs or eNBs and in 5G as gNodeBs (gNBs). The radio interface of the BSs is responsible for supporting the following information transfer mechanisms on the radio channel:

  – Broadcasting of control signaling in the cell coverage area: This information aims to allow UEs to detect the presence of the BS and to know its basic operating parameters (e.g., the maximum power that UEs can use in the cell). It also informs the identity of the operators that can be accessed through that BS. Furthermore, it forces the UE that does not have an established control connection to initiate access to the network in a procedure known as paging.

- IP packet transfer over the radio channel: The data channel services between an g/eNB and a UE (called Radio Bearers or RBs) are designed to support IP traffic. In order to optimize the forwarding of such traffic over the radio interface, RB services host functions such as IP packet header compression.
- Dedicated control signaling transfer: Establishing a dedicated control connection is essential to manage the use of bearer services and perform any signaling management with the core network (e.g., UE registration). The control connection is carried out using the Radio Resource Control (RRC) protocol. This protocol not only manages the establishment or release of bearer services but also controls the well-known handover mobility mechanisms that allow a UE to switch cells while keeping the control (signaling) connection active and the radio bearer services it uses. UEs maintaining a control connection to RAN are said to be in connected or active mode, as opposed to the so-called idle mode where the terminal does not have an RRC connection and monitors the control information broadcast over the network.
- Forwarding of user packets: Each bearer service has an associated QoS profile that must be satisfied by the correct configuration of the radio protocols and the proper operation of the radio resource management mechanisms (e.g., scheduling).

The mobile **Core**, with the main purpose of enabling the following functionalities (among others):

1. IP connectivity to a data network (typically the Internet) and basic telephony services (voice or video conferencing).
2. Ensuring that the connectivity complies with the Service Level Agreement (SLA) agreed with the user.
3. Manage the mobility of the users in such a way that the services are not interrupted while they move around the area of coverage (handover).
4. To carry out end-to-end management of the network signaling plane for charging, monitoring, etc.

The mobile core in 4G or Long Term Evolution (LTE) is called Evolved Packet Core or EPC, while in 5G, it is called NG-core. Although both are native to IP, the main differences in their architecture are that in 5G, the control and user planes are separated into distinct functions. Besides, virtualized deployment is enabled in 5G, and entities such as the network chunk selection function (NSSF) are added to facilitate advanced chunk management.

2.1.1 RAN protocol architecture

The radio protocol architecture of the Radio Access Network is based on the OSI reference model (Figure 2.2). This model describes seven layers of communication and introduces interaction between the lower and upper layers. As such, in the RAN network, IP packet forwarding (layer 3) between the g/eNB and the UE via the radio interface is supported by a link layer (or layer 2) and a physical layer (layer 1). In the case of the cellular network, the link layer is composed of three sub-layers: Packet Data Convergence Protocol (PDCP), Radio Link Control (RLC) and Medium Access Control (MAC).

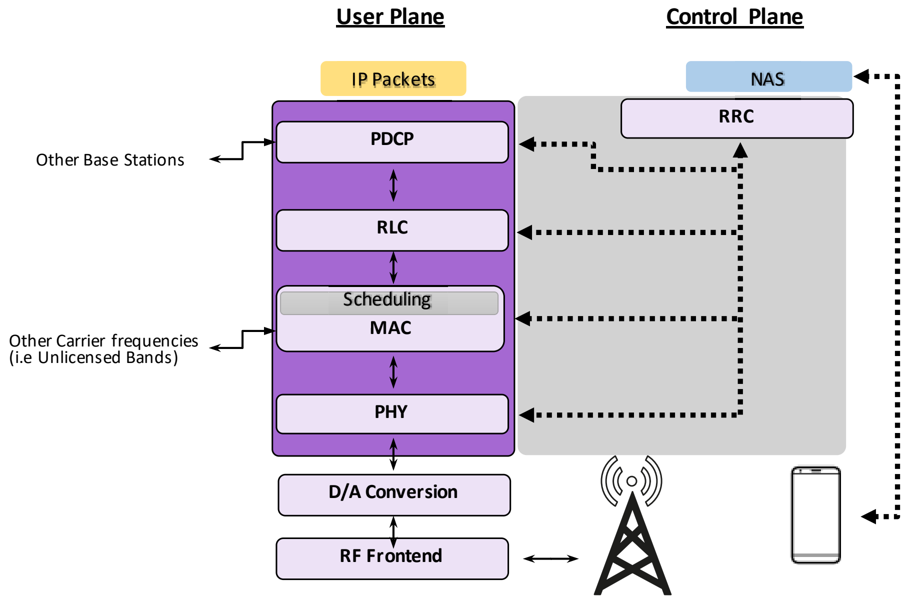

Figure 2.2: RAN protocol architecture.

The architecture is further subdivided into user plane (U) and control plane (C) as shown in Figure 2.2. The user plane is responsible for all protocols needed to transfer user data. The control plane manages the data transfers in the network and the connections of the user equipment to the access network. The main characteristics of the different layers/sub-layers are described below:

- Packet Data Convergence Protocol (PDCP). It is the top layer of the RAN protocol responsible for providing the access point to the Radio Bearer (RB) service. In other words, IP packets of user traffic are delivered and received through the service provided by the PDCP layer. Its main functions include the compression of IP packet headers and the encryption of the information to guarantee confidentiality and integrity. The header contains a sequence number that identifies the IP packet sent, allows for an orderly delivery of IP packets at the receiving end, and detects possible duplicates (caused, for example, in a handover process). Each RB service has an associated PDCP entity.

- Radio Link Control (RLC). The RLC layer allows PDCP packets to be reliably sent between the eNB and the UE. For this purpose, the RLC layer supports error correction functions through Automatic Repeat ReQuest (ARQ), concatenation, segmentation, and reassembly, ordered delivery of PDCP packets to higher layers (except during the handover mechanism), duplicate detection, and protocol error detection/recovery. Each radio bearer service has an associated RLC entity.

- Medium Access Control (MAC). This is the entity in charge of controlling the access to the radio channel. To this end, the MAC layer supports dynamic scheduling functions between UEs according to priorities and multiplexes the packets of different RB services on the transport channels offered by the physical layer (a transport channel can be shared by several bearer services of one or several UEs). It also performs error control through Hybrid ARQ (H-ARQ). The transfer services provided by the MAC layer to the RLC layer are called logical channels. There is only one MAC entity per cell. In the case of using unlicensed bands where contention protocols are implemented in addition to the MAC layer, the scheduling mechanism is common with licensed bands.

- Physical layer (PHY). This layer is responsible for the actual transmission over the radio channel. It enables channel coding, modulation, processing associated with multiple transmit/receive antenna techniques, and the signal mapping to the appropriate physical frequency-time resources. The transmission scheme of the uplink is based on an FDMA single-carrier scheme. By contrast in the downlink is Orthogonal FDMA (OFDMA). The transfer services the physical layer provides to the MAC layer are called transport channels. There is only one physical layer entity per cell.

Regarding the control plane, the link layer protocols are the same as the user plane, but the network layer implements specific protocols as follows:

- Radio Resource Control (RRC): This layer allows the establishment of a control connection between the eNB and the user equipment through which several essential functions related to the management of the operation of the radio interface are carried out. The RRC layer functions include

1. Bearer services management mechanisms(e.g., signaling for the establishment, release, and modification of radio bearers)
2. Mobility functions support (e.g., handover signaling)
3. Broadcasting system parameters and alerting functions of terminals that do not have an established RRC connection (e.g., sending alerts via the paging channel). The handover service provided by the PDCP layer for sending RRC protocol signaling messages is called Signaling Radio Bearer (SRB) service.

- Network Access Stratum (NAS) signaling protocols: NAS protocols interoperate between the core network's session management function/mobile management entity and the UE. The messages of these protocols are carried transparently on the radio interface encapsulated within the data part of the RRC messages. Its main functions are the authentication, authorization, mobility management of terminals that do not have an established RRC connection, and the management of network bearer services.

2.1.2 Specifications for unlicensed spectrum operation

Introduced as part of 3GPP Release 16 specifications, 5G New Radio Unlicensed (NR-U) [28] is an evolution of the 4G LTE License Assisted Access (LAA) standards, first described in 3GPP release 13 [29]. As currently defined, NR-U supports three deployment modes [30] illustrated in Figure 2.3:

- Carrier Aggregation: The unlicensed spectrum is used only to augment downstream user plane capacity as conceived in LAA. Control plane data is transported over licensed spectrum only.
- Dual Connectivity: supports both upstream and downstream user plane traffic over the unlicensed spectrum. This operation mode is built on extended LAA (eLAA) operation, introduced in 3GPP release 14. Again, this is designed for traffic offloading and not for coverage, so control plane traffic is transported only over the licensed spectrum.
- Standalone: represents the first time the 3GPP has defined a mode of operation that relies solely on unlicensed bands for control and user plane traffic. This implementation has been built based on LTE technology developed by the MulteFire Alliance [31, 32].

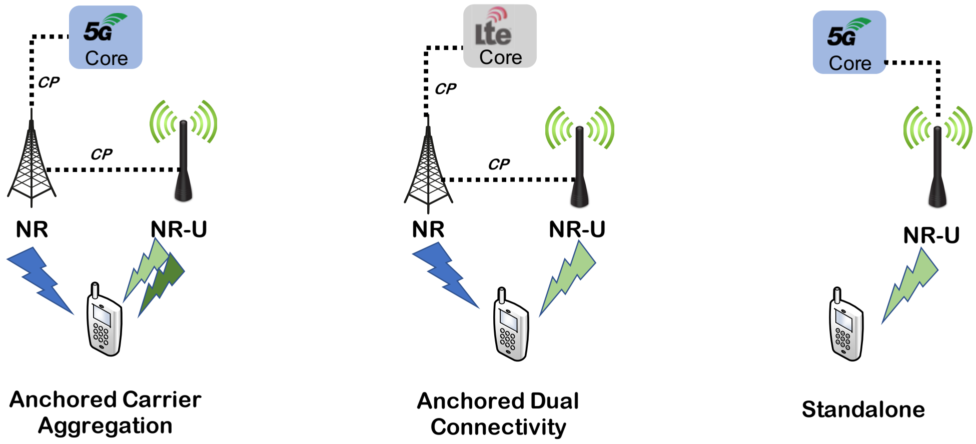

Figure 2.3: NR-U deployment modes.

With standalone mode in NR-U, any dependency on licensed network operators is eliminated, and it is open for implementation by private enterprises, managed service providers, or network systems integrators. This feature enables private 5G deployments supporting new consumer and Industry 4.0 applications demanding secure, low-latency, reliable, high bandwidth connectivity to densely populated end-points. While the carrier aggregation and dual connectivity modes are designed to operate in the 5Ghz spectrum, the NR-U standalone mode has been built for all sub-7 GHz mid-band ranges plus high-band frequencies in the 57 to 71 GHz ranges that are opening up around the globe. Support for these mmWave bands is being defined within 3GPP Release 17 specifications.

The frequency ranges in which NR-U is deployed - in any mode of operation - dictates how it is implemented. As with LAA, the primary concern of operating NR-U in the highly utilized 5 GHz bands is ensuring harmonious coexistence with other mobile technologies, like Wi-Fi. The introduction of a 5G NR radio access network (RAN) should cause no more impact on an existing Wi-Fi system than adding another Wi-Fi access point. While NR-U employs the 5G NR PHY layer and therefore enjoys the benefits of evolutions such as multi-numerology and mini-slots, the medium access control (MAC) layer protocols for processes such as channel access have been modified to align with Wi-Fi. Once again, this mechanism follows the principles of the LAA predecessor and employs the same contention-based Listen Before Talk (LBT) protocol used in 802.11 to ensure equal access to available channels. This technique is referred to as asynchronous NR-U operation and does limit some of the benefits of 5G NR, such as the ability to support ultra-reliable low-latency communication (URLLC) [33].

New opportunities to improve spectral efficiency and the performance of new applications are emerging as other less populated frequency ranges become available for NR-U standards. In the EU, the US, and South Korea, the 5.925GHz to 7.125GHz frequency range is now being opened up for unlicensed devices. In this context, the FCC and ETSI support the unlicensed use of the 6 GHz band for universal access for low power (under 30 dBm) indoor applications. In addition, the U-NII-5 and UNII7 sub-bands can operate outdoors at the same levels currently employed by 5 GHz systems. Still, they must use an automated frequency control (AFC) system, like the Spectrum Access System (SAS) employed in the citizen broadband radio service (CBRS). As a result, interference with existing ground-to-space and point-to-point microwave links that also operate at these wavelengths is avoided.

Although 802.11ax (WiFi 6) also uses the 6 GHz band, it is considered a greenfield spectrum when operating inside a building. The abundance of spectrum available, together with the absence of any interference, coupled with the natural isolation of the signals due to their low propagation rates through the air and physical structures, means that interference will be negligible. Outdoors, the incorporation of AFC ensures that there will be no interference from alternative radio access technologies.

This allows NR-U devices operating in the 6 GHz frequency range (or above) not to be impaired by the strict LBT protocols adopted for harmonious coexistence in the 5 GHz bands, which have been classified by 3GPP in several categories.

- LBT CAT1 that does not require detection;
- LBT CAT2 with a fixed detection period;
- LBT CAT3 with random backoff and fixed contention window;
- LBT CAT4 with variable detection periods and random backoffs with variable contention window

As shown in Figure 2.4, NR-U devices can transmit if the Clear Channel Assessment (CCA) procedure indicates that the channel is idle; otherwise, the wireless device must defer transmission. The back-off time plays a key role in the equal sharing of channel time between Wi-Fi and NR-U. It is worth mentioning that Wi-Fi does not implement the deferral periods in the carrier sensing mechanism but performs an exponential back-off of the contention window, which LBT does not execute. As part of the LBT procedure, Wi-Fi devices use a combination of energy detection and reception of a known modulated and coded signal called a preamble.

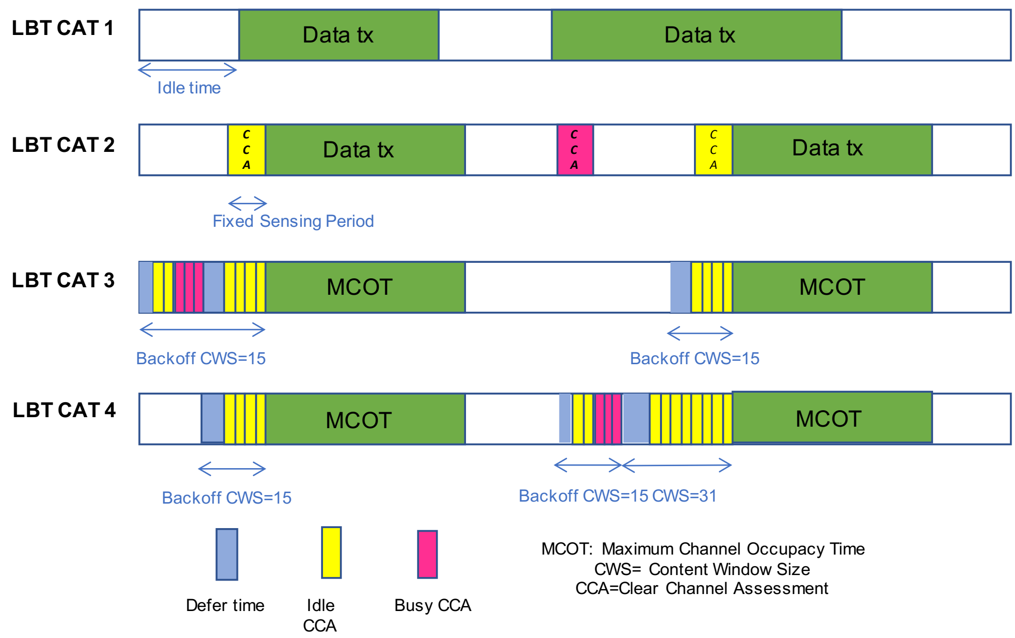

Figure 2.4: Listen Before Talk 3GPP Categories

In light of these features, Category 4 (CAT4) LBT serves as the baseline for 5 GHz operation, forcing strict back-off in accordance with carrier sense multiple access/collision avoidance (CSMA/CA) procedures. NR-U can employ CAT1 LBT above the 6 GHz range, where channel access is immediate and requires no LBT. Instead, channel availability can be determined by simple energy detection, thereby permitting rapid access to transmission channels in support of low latency automation and IoT applications.

2.2 Management of Celullar Networks

Since the genesis of cellular networks, management has been one of the critical aspects of their deployment, operation, and maintenance. The effectiveness of this set of tasks, therefore, is what enables mobile operators to make their infrastructure profitable. The multiplicity of specific hardware components, the high dynamicity of the radio environment, and the fluctuating demands dependent on human behaviour continue to be one of the biggest challenges.

MNOs have an extensive infrastructure consisting of equipment (i.e. pico, micro and macro cells) and applications from various vendors. A layered approach is used to manage these complex networks. The idea is that management decisions at each level are different but interrelated. There is a tendency for the network management functionality to be continuously changing, and these changes or adjustments are visible in the network elements.

In order to address these issues, standardization bodies have introduced the concept of SON (Self-Organizing Networks) to enable automation of part of the configuration and optimization processes. A typical area of application is heterogeneous deployments, where the integrated macro, micro and pico scenario can make local optimization activities extremely complex and manageable only through automatized solutions.

The 3GPP body explained the Self-Organizing Networks concept with LTE in Release 8. In [34, 35] the use cases transposed (some derived from the NGMN activity) and the architectural description of the RAN functionalities supporting SON are reported. These, in turn, are classified into the following categories:

1. **Self-configuration**: Performs the tasks necessary for the start-up and proper configuration of the network elements. These, in turn, must be able to perform initialization, authentication, and connection establishment with the OSS. They must also be able to exchange information with adjacent elements. The following use cases included in the 3GPP standard are worth mentioning

    - Plug & Play: IP address allocation, authentication, software & configuration data download from OAM, establish connectivity
    - Setting of new g/eNodeB radio parameters: Physical Cell ID (CID) automatic configuration, handover & cell selection thresholds, power settings, etc.
    - Setting of g/eNodeB new transport parameters
    - Automatic Neighbor Relation (ANR)

2. **Self-optimization**: Once the cellular network is operational, it performs an adjustment of the network parameters to maximize performance. This category includes multiple use cases such as the following:

    - Optimization of the neighboring cell list (intra/inter frequency and inter system).
    - Cell Interference Coordination
    - Handover parameter optimization

- QoS optimization
- Power saving optimization
- Load balancing

3. **Self-healing**: It groups a set of functions in charge of preventing and repairing any problem that arises, even if it is not directly reported in the form of an alarm. These are maintenance tasks that deal with degradation detection, outages, failure causes, diagnosis, recovery and/or compensation actions.

4. **Self-planning**: This term encompasses configuration and optimization capabilities to set up entire parts of the network in order to increase the service quality or coverage.

Three architectures have been defined for SON implementation [36]:

- Centralized: In this architecture, the SON functionality is enabled only in a reduced number of locations at the management level (OSS) from where they control all network elements. Its operability on a temporal scale ranges from hours to days.
- Distributed: According to this model, the algorithms are executed directly on the network elements, having access only to the information collected by the network itself. Their action includes periods of time that can be of the order of seconds.
- Hybrid: In this type of architecture, SON algorithms are found both in the network elements and at the management level. It adds a level of complexity by having to coordinate two types of algorithms, although it is advantageous in multivendor or virtualized deployments where orchestration plays a fundamental role.

With regard to the modes to support automated service assurance on the basis of which SON algorithms operate, there are two approaches [37]: The open-loop design scheme is the approach that is in operation in most of the algorithms deployed in the current OSS. According to this approach, SON algorithms are responsible for identifying possible changes in the network, and it is the responsibility of the operations engineers to accept or reject this recommendation. By contrast, the ultimate goal of autonomous network management systems, including SON, is to operate in closed-loop mode [38]. According to this way of proceeding, and as shown in Figure 2.5, the SON system is in charge of monitoring the network constantly by storing different metrics, counters, alarms, etc.

These databases are analyzed by the algorithms based on the triggers or events that are considered relevant. Once the solution is identified (e.g., to a failure or degradation), the command sequence is sent and run automatically. Subsequently, the evolution and the effects on the counters are observed in a new monitoring process, and the executed commands are maintained or reversed (e.g., because the cause of failure has disappeared or the algorithm output has not produced the desired effect).

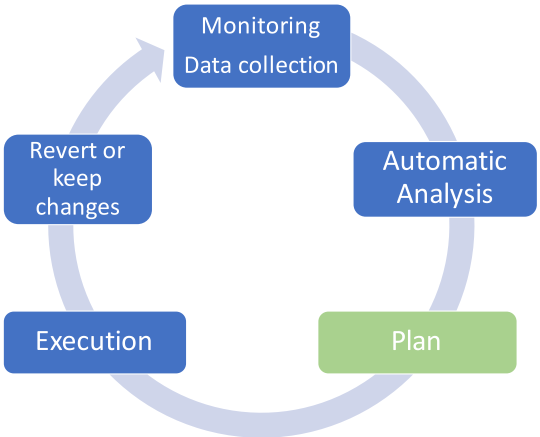

Figure 2.5: SON Closed Loop Operation scheme

The different algorithms in charge of implementing the SON procedures are fed by several data sources, most of which come from the network management systems. Among these resources of input, the following are worth mentioning:

- Configuration parameters (CM): This consists of a record of values for the different variables that make up the setting of each network element.
- Performance parameters (PM): This is a type of information presented in the form of counters or indicators of the performance of a network element over a time frame that is reported periodically.
- Failure Parameters (FM): Collects network notifications in the form of alerts/alarms that indicate that there has been some kind of failure (e.g., hardware or connectivity) in a particular element or segment of the cellular network.
- Call Detail Records (CDR): Contains anonymized information on the activity of each UE when it has made use of the network (e.g., when a call is initiated). Sometimes they may include geolocation by triangulation, which is often not very accurate.

- Drive Tests (DT): It is a sampling that is performed with specialized equipment mapping the areas with coverage that collects radio parameters in the terminal (RSRP, RSRQ, RSSI) and optionally another type of performance test in the application layer. It usually contains GPS geolocated information.
- Key Performance Indicators (KPI): These are indicators that are calculated from combinations of other counters in order to have a meaningful measure of network performance.
- Contextual Information: This type of data measures those phenomena that, although they do not occur within the network, have a considerable impact on its performance. It can be information about the mobility of a group of people, activities taking place in a specific area, and other external aspects that condition the use and operation of the cellular network

2.3 State of the art of main research areas

2.3.1 Social and location awareness

As mentioned in previous sections, SON mechanisms, until the advent of 5G, have based their operation on indicators mostly coming from the mobile network itself. Whether in the form of KPIs, alarms, or mobile traces, the data usually used to train ML algorithms are based on actual network sources.

In this sense, the Network Data Analysis Function (NWDAF) recently introduced by 3GPP [39] is a new core function that is responsible for providing network analysis information at the request of the Network Functions (NF). Helping, for example, the Policy Control Function (PCF) to decide how to manage traffic based on existing resources according to the guidelines it deems appropriate. While the inclusion of the NWDAF [40], including localized data, is certainly promising, it is still in the early stages of development to be able to take full advantage of it at a network management level [41].

There is nevertheless a vast set of variables external to the cellular network, called contextual [42], that have a significant impact on performance [43]. Some well-known examples would be the occurrence of social events (such as concerts, sporting events, fairs), weather conditions, urban and road layout, traffic, population density, position of different users, etc., which directly condition service provision needs and network elements. They also influence the quality of service provision at a general level and for each user and is often the cause of network failures and degradation.

So far, this context-aware approach [9], i.e., the use of information variables external to the cellular network to support its management, has been constrained by the lack of available information sources, their heterogeneity, and the lack of adequate mechanisms for the acquisition and processing of such information. In recent years, however, the availability of digitized contextual information has grown exponentially in the form of social networks, databases, web pages, calendars, and news feeds.

The usefulness of context data has been demonstrated by multiple works carried out where it is applied in tasks outside the cellular operation. Some recent illustrative examples are [44] where the use of geolocated Twitter allows to find out areas of traffic demand or [45] that manages handover in a mobility environment in vehicles based on atmospheric or environmental conditions obtained from open sources available on the Internet. More recently, in [46] the possibility of using information from social networks for better QoE management based on user preferences is envisioned.

The complex tasks of a virtualized network implementing the slicing feature make it necessary to incorporate context information. In this sense, the work [47] is, to date, the only reference where a contextual source integration framework is proposed in the network operation. It also presents not only the acquisition but also the processing through an association with the reference indicators used in current SON mechanisms. Hence, an excellent opportunity to provide future cellular networks with anticipatory capacity [48] through the use of digital social information is thus demonstrated [49], being one of the cornerstones for the development of native AI beyond 5G and 6G management platforms [50].

2.3.2 User-Centric monitoring

Nowadays, Quality of Service (QoS) is the most widely used metric in classic mobile network management models [51]. By means of network layer measurements, different metrics are analyzed to determine network performance (KPIs): delay, jitter, error probability, packet loss, available bandwidth, etc. Although the use of these reference metrics is helpful for gaining insight into the large-scale operation and the problems that may arise during it, they are clearly insufficient to determine the users' perception of the service offered at any given time.

In this context, various techniques have been proposed to establish the degree of perception of the quality of the different services (known as QoE), incorporating objective and subjective criteria. According to ITU-T [52], QoE is defined as "the overall acceptability of an application or service, as perceived subjectively by the end-user". Assuming that this perception may vary from one subject to another, taking into account a series of factors, including the user's expectations.

This is, therefore, a complex problem on which an extensive bibliography has been developed, proposing to complement QoS with the user-centered approach so that the network is able to satisfy both the requirements and the expectations of a large number of users. Taking all these assumptions into account, it can be deduced that efficient end-to-end QoE management would allow users to benefit from an adequate satisfaction of their expectations, thus inclining them to adopt new services and supporting a higher degree of digitalisation development [53].

The future mobile networks, as a fundamental part of the service delivery chain as applications, including user device manufacturers, content providers, cloud computing platforms, etc., must be able to anticipate quality issues before customers perceive them. ML algorithms based on a large amount of data that the network is capable of incorporating and storing present fundamentally two use cases for RAN management:

On the one hand, given the ever-increasing abundance in the availability of multidimensional data collected by the network, a reliable and robust prediction of service patterns (in the form of Key Quality Indicators (KQIs) as objective quantifiers of QoE [54]), user trajectories, possible interference, or performance anomalies among others is enabled. The accuracy of these predictions will lead to much more efficient management and assured quality customization.

On the other hand, data analytics techniques based on ML mechanisms allow optimization and decision-making that are extremely difficult to solve by modeling due to their computational complexity.

2.3.3 Unlicensed Spectrum provisioning

As discussed in previous Section 2.1.2, there have been extensive efforts to achieve interoperability of cellular networks with unlicensed bands [55, 56, 57, 58, 59]. Such capability assumes that it is a shared resource that should be easily accessible, fair to all spectrum users, and in no way privilege any particular technology [60]. Therefore, by operating cellular networks such as LTE and NR in the unlicensed bands, significant benefits in several aspects can be achieved. A number of the gains derived from this operation are as follows:

- High capacity, spectral efficiency, and data rates : Due to the addition of the unlicensed spectrum, the combined spectrum bandwidth of an MNO increases. Because the capacity is directly proportional to the available channel bandwidth, the use of the unlicensed spectrum in a cellular network helps increase its overall capacity, spectral efficiency, as well as data rates per user.

- Data offloading: As there is no cost from using an unlicensed spectrum, by operating an MNO in both the licensed and unlicensed spectrum bands, the demand for high capacity and data rates per user of the MNO can be served at a low average cost per bit transmission, resulting in improving its cost-efficiency.
- Cost-efficiency: An MNO can configure its indoor small cells to offload all or a major portion of its user traffic over the unlicensed spectrum.

Several technical issues still remain unaddressed across different layers for the operation of cellular (i.e., LTE-U, LAA, and NR-U) and IEEE 802.11 standards (i.e., WiFi and WiGig) [61, 55]. There are proposals for coordinated [62, 63] and uncoordinated operation [64][59]. Major constraints to designing an efficient coexistence mechanism include:

- Lack of inter-Radio Access Technology (RAT) coordination
- Inter-cell interference management
- Independent resource allocations from one RAT to another, and different Physical Layer (PHY) protocols

On the other hand, Medium Access Control (MAC) and Physical and MAC layer procedures of cellular and IEEE 802.11 technologies have distinct designs [65] such as:

- The transmission power, Modulation and Coding Schemes (MCS), and error correction codes differ
- Cellular standards use Radio Link Control Layer with Hybrid Automatic Repeat Request (HARQ). In contrast, WiFi, for example, uses Automatic Repeat Request (ARQ) mechanisms to recover packet losses.
- In the case of the MAC layer procedure, cellular technology is an allocation-based mechanism, whereas an IEEE 802.11 (e.g., WiFi) technology is a contention-based mechanism
- Cellular RAN operates with continuous data transmission in consecutive frames using a centralized scheduler. By contrast, WiFi technology uses opportunistic communication using Distributed Coordination Function (DCF).
- CSMA/CA protocol to detect the energy level in order to get access to a channel is used by DCF.

In summary, given that, unlike in the licensed bands, the unlicensed spectrum is operated in a discontinuous and opportunistic manner, cellular standards are forced to include LBT. Notwithstanding, such inclusion results in reduced efficiency and flexibility in Radio Resource Management (RRM) [56, 66]. For this reason, analysis of real-world coexistence deployment data on the performance and behaviour of these deployments is still scarce, despite the fact that some ad hoc deployments have been carried out [59].

Besides, the problem of fair coexistence of NR-U and the prediction of the performance of the different supported services (video-streaming, FTP, web browsing...) in coexistence deployments are still open questions [67].

Part II

Publications

Chapter 3

Research outline

Content

This chapter is structured in two sections. The first section describes the relationship between the challenges identified and the objectives achieved in each of the reported research papers. It also justifies the thematic connection between them and the sequence followed in their presentation.

The second section summarizes the research methodology followed during the development of this thesis. This section describes the tools used in the research. For more details on the implementations carried out with these tools, please refer to Appendix A.

3.1 Description of the publications

Each journal article composing this thesis addresses at least one of the previously presented challenges. Figure 3.1 summarizes the scenario and the relation of the papers to the challenges and objectives, indicating how they are organized in this report. In particular, this figure presents each paper as a unique block, specifying the achieved goals, the used data sources, and the interaction among the techniques developed in each work.

The order has been chosen based on the extent of the modifications that need to be undertaken for the actual implementation of the proposed approaches in current cellular networks.

Chapter 4 presents a paper that proposes a framework for incorporating positioning into user traces to form images of network state from which to perform automatic diagnostics. Second, an article is included that presents a novel method for predicting social events based on network metrics using neural networks.

Chapter 5 contains the publication proposing a framework for user data collection using virtualized probes in environments with a high concentration of people at events and also includes event impact analysis using an extensive time-series measurement campaign.

Chapter 6 includes publications related to the management of unlicensed bands in indoor environments. On the one hand, an evaluation of how ultra-dense indoor environments in coexistence with WiFi affect the service perceived by the user is performed. On the other hand, a inband signaling optimization of the 3GPP LBT CAT4 protocol is proposed.

The specific content of each of the papers is briefly summarized in the following subsections.

Figure 3.1: Map of challenges

3.1.1 Social-aware forecasting for cellular networks metrics

In order to acquire true social context-awareness, cellular networks must incorporate information from outside the network itself that allows determining the type of mobility and user concentration patterns. In this sense, the more the cellular network is able to anticipate these types of events that have a substantial impact on its operations, the better it will be able to plan and manage itself.

The article presented in section 4.1 makes use of currently available resources such as open sources of events and complements them with information collected by operators in the form of KPIs. It proposes a method to relate the impacts on network operations to the planned concentrations of people produced in the events. On the one hand, it predicts the level of impact that the selected KPIs will have, and on the other hand, it makes it possible to anticipate such degradations well in advance. This forecast is aligned with Objective 1. To this end, a novel stacked exogenous autoregressive nonlinear autoregressive (NARX) approach is adopted, specifically defined to allow the use of information from social events to improve metrics forecasting.

Subsequently, a novel system is presented to support these mechanisms, including a detailed description of its functions and variables. In addition, the methodology for estimating its hyperparameters, training, and forecasting application is established. The predictions provided by the system have been methodologically evaluated using data from a real cellular network and are compared with a non-social context-aware approach. The performance of the method yields promising results for application.

3.1.2 A novel synthetic image-based approach for location-aware management of cellular networks

Chapter 4 introduces the approach that aims to enable social context awareness that allows cellular networks to efficiently adjust their resources based on the usage derived from this behavior. One of the enabling technologies that are in the mature stage of development is those that allow the position of users to be determined. However, while there are some proposals in the literature on the use of positioned network traces in automatic network management, their advanced processing can offer many more advantages. In this sense, the radio frequency and network performance maps obtained in Drive Tests are insufficient since they only reflect a particular state of the network at a given time. On the other hand, the management of traces in the form of time series is highly complex when analyzing patterns.

In this publication (section 4.2), the establishment of a framework to exploit the information contained in such traces positioned is proposed for tasks where automatic management may be able to detect inadvertent failures due to complex interactions (Objective 2).

To achieve this, a method is established to transform the traces into synthetic images that reflect the network state by highlighting those elements that are decisive for a given task. The construction of such images offers flexibility to determine the necessary localization accuracy and periodicity of sampling as well as other relevant parameters. Once the synthetic network images or NSI are created, they take advantage of the power of Deep Learning image classification algorithms to determine problem situations that have been labeled in a supervised manner. Thus, an example of an automatic diagnosis application based on the NSI-based framework is shown.

The methodology used is the simulation of a real airport environment where several LTE indoor stations are located and where the location of each user is known. The results show that the approach outperforms the accuracy achieved by RF map-based methods.

3.1.3 Cellular network radio monitoring and management through virtual ue probes: A study case based on crowded events

As mentioned above, in the experience of MNOs, massive events have a significant impact on the cellular network. Although this impact is significant from a KPI-based management point of view, where this effect is really felt is in the service perception of the users.

This is where network management should incorporate objective QoE metrics on which to make decisions. This User-Centric monitoring approach is the one proposed to be enabled in the article in section 5.1 according to Objective 3.

Based on the maturity that SDN, SDR, and NFV virtualization technologies are reaching, a non-invasive QoE incorporation method based on virtualized probes is proposed. The perception of the users is a quality to be objectively measured through scheduled data collection campaigns based on the execution of various applications on the probes (FTP, Ping, Video, Speed Test).

To test the feasibility of the framework for the automatic incorporation of user data into the cellular network, two virtualized probes are deployed in the stadium of Trondheim (Norway). Subsequently, an extensive measurement campaign is carried out on days when an event is hosted in compliance with Objective 4.

The QoE performance of an event is experimentally tested, and differences can be observed depending on the operator's network, the service, and the time at which it is measured (before, during, or after the event). This information thus contributes establishing baselines to prevent future service degradations. Thus, the article summarizes the implications of such a systematic collection and the areas where it could be included in terms of automatic cellular network management.

3.1.4 KQI performance evaluation of 3GPP LBT priorities for indoor unlicensed coexistence scenarios

The traditional proprietary use of frequency bands inherent to cellular technologies makes it an extremely scarce resource. Especially in situations where there is a concentration of users and where application requirements are high, greater spectral availability is imperative. Thus, the use of unlicensed bands is postulated as one of the most plausible alternatives to incorporate capacity in cellular networks dynamically.

In the article contained in section 6.1, a realistic assessment of the quality of services provided to users in an environment of provisioning the indoor unlicensed bands in coexistence with WiFi is performed. First, in accordance with Objective 5, a full-stack simulation tool is used to extract realistic results and has been adapted to simulate a scenario where the use of unlicensed bands avoids service degradation in terms of QoE. Subsequently, an evaluation of the possibilities offered by the LBT protocol in coexistence with WiFi in services such as FTP and video streaming is carried out in accordance with Objective 6.

An ultra-dense indoor scenario is recreated where FTP and video-streaming traffic is combined. Also, the unlicensed band only uses the downstream shared channel supported by the upstream licensed channel. Following the indications of the 3GPP standard, the LBT protocol parameter configurations have been tested, comparing QoE and fairness ("fairness") with respect to WiFi. Based on the simulations, it is concluded that with the parameters set by the standard, there are options that are unfair with regard to WiFi and that there are preferred configurations for improving the performance of both services. These findings leave room for possible automatic optimizations based on environmental conditions in real-time.

3.1.5 Assessing the impact of DRS signaling in unlicensed indoor coexistence scenarios

Complementary to the article in section 6.1 and included in the chapter 6 that enables the approach focused on the use of unlicensed bands, the work presented in section 6.2 proposes a signaling optimization mechanism as outlined in Objective 7.

The role of the type of DRS signaling that is broadcast on the unlicensed shared channel is analyzed. Under different user and base station loading conditions and in coexistence with WiFi, the impact of such signaling on service performance is evaluated. As a result, it has been identified that the presence of such signaling impairs fairness with respect to WiFi and that the suppression of such signaling implies a degradation of service. An alternative CDRS compensation mechanism is then proposed that improves throughput by 10 percent by increasing fairness by 25 percent.

3.2 Research methodology

The contributions reported in this thesis were conducted throughout a structured research methodology, characterized by an engineering-oriented approach. In particular, this research methodology is divided into the following steps (see Figure 3.2).

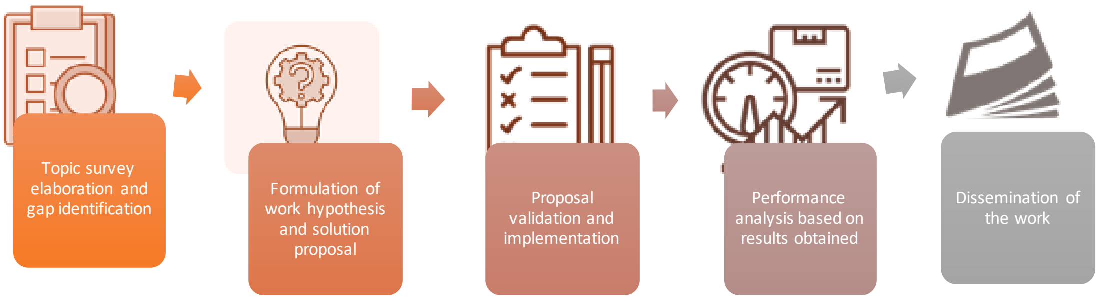

Figure 3.2: Methodology structure

Given the nature of the engineering-oriented research to the future implementation in commercial cellular network management systems, a methodology that combines the classical approach with a more applied focus oriented to innovation has been followed. Thus, a sequence of five main steps has been identified, which are described below.

1. **Topic survey and gap identification**

   As a first step, it is necessary to clearly define which problems in the field of cellular networks are relevant to solve or require in-depth study.

   On the one hand, a thorough study of state of the art is required through a careful review of the existing literature on network management.

   On the other hand, some of the most promising trends for the advancement of the field have been identified through participation in research projects and exchanges with fellow researchers and industry experts.

   From all these contributions, starting from user-centric management, interesting issues in crowd management, perception of quality of experience, and operation in unlicensed bands have been identified.

2. **Formulation of work hypothesis and solution proposal**

   Once the relevant technical knowledge has been acquired, the working hypothesis is formulated, and several alternative solutions are proposed.

   In addition, the existing literature is consulted in a more detailed way about possible techniques that propose the resolution of the hypotheses that have been raised.

   Moreover, preliminary evaluations, either by means of simulations or measurement campaigns, are crucial in the reformulation of the hypothesis.

   The exchange of information with supervisors and experts in the field completes this stage in order to validate the feasibility of its future implementation in real systems.

3. **Proposal validation and implementation**

   Given the large number of variables and the degree of randomness present in the cellular network environment, a purely theoretical approach is clearly insufficient.

   This fact leads to the fact that all the proposals of this thesis have to be verified either with full-stack simulations close to reality following the Monte-Carlo method or with measurements taken on deployed commercial networks.

Regarding the first option, it is the one that has been chosen for the approach of operation in unlicensed bands. The radio models underlying the simulator have been implemented in line with the stochastic and complex nature of cellular networks. In order to obtain significant statistical significance, multiple realizations of the scenarios with different starting locations and UE mobility have been performed.

4. **Performance analysis based on results obtained**

   Once it has been possible to test the initial hypotheses either experimentally or via simulations, the impact in terms of performance indicators of the proposed systems has been assessed. For the development of this phase it is necessary to analyze the results obtained from a statistical and sensitivity analysis point of view. In this way it is possible to identify any unexpected effects or borderline cases that were not taken into account when the problem in question was posed. Thus, as part of this process, readjustments have been made in the design of the proposed frameworks or techniques.

5. **Dissemination of the work**

   To conclude, a compilation of all the most relevant aspects of the proposed methods and solutions are presented in writing in a concise but as complete form as possible. These reports form part of the deliverables of the projects whose framework has supported the research, as well as in the form of scientific publications in conferences and high impact journals.

   In addition, the dissemination work has resulted in the participation in different European project meetings, attendance at national and international conferences and events such as the Mobile World Congress 2019.

Chapter 4

Social and Location Awareness

4.1 Social-Aware Forecasting for Cellular Networks Metrics

[68] J. Villegas, E. Baena, S. Fortes, and R. Barco, “Social-Aware Forecasting for Cellular Networks Metrics,” *IEEE Communications Letters*
DOI: 10.1109/LCOMM.2021.3065812

Abstract: It has been long established that crowds generated by social events (e.g., sports matches, parades, fairs...) produce a high impact on cellular network service. However, to estimate such an impact, it is necessary to use data sources classically outside the mobile operator control. In this way, and following a social-aware approach, the forecasting mechanisms should be able to combine both social and network information to obtain reliable predictions. To this end, the present work develops a complete system for its use in the prediction of cellular metrics (e.g., connections, throughput...). The performance of the proposed solution is evaluated in a real cellular network, showing the capabilities of the approach to provide accurate forecasting.

4.2 A novel synthetic image-based approach for location-aware management

[69] E. Baena, S. Fortes, F.Muro, C.Baena, and R. Barco, “A novel synthetic image-based approach for location-aware management of cellular networks,” *IEEE Network*, 2022. Under review
DOI: 10.1109/MNET.2022.XXX

Abstract: Traditional approaches to cellular network troubleshooting have generally relied on alarm analysis or performance metrics to identify the cause of network failures. In contrast to this scheme, the increasing availability of positioned user equipment traces implies a much richer data source for cellular network management. The map-like generated is much more complex to analyze than classical time-series- style cellular metrics. Therefore, its application for problem-solving still relies heavily on direct human inspection. On the other hand, image processing algorithms have shown extraordinary progress in recent years, being able to establish patterns undetectable to the human eye. In this way, the present work proposes and implements a novel location-aware framework that defines the processes necessary to transform the positioned mobile traces into a image-like format, called Network Synthetic Images (NSI). These NSIs are used as input for deep learning image processing mechanisms in order to provide a simplified cellular network management. The proposed system is evaluated under different conditions and configurations, showing the capabilities of the approach to support fault diagnosis.

A novel synthetic image-based approach for location-aware management of cellular networks

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***Abstract*—Traditional approaches to cellular network troubleshooting have generally relied on alarm analysis or performance metrics to identify the cause of network failures. In contrast to this scheme, the increasing availability of positioned user equipment traces implies a much richer data source for cellular network management. The map-like generated is much more complex to analyze than classical time-series-style cellular metrics. Therefore, its application for problem-solving still relies heavily on direct human inspection. On the other hand, image processing algorithms have shown extraordinary progress in recent years, being able to establish patterns undetectable to the human eye. In this way, the present work proposes and implements a novel location-aware framework that defines the processes necessary to transform the positioned mobile traces into a image-like format, called Network Synthetic Images (NSI). These NSIs are used as input for deep learning image processing mechanisms in order to provide a simplified cellular network management. The proposed system is evaluated under different conditions and configurations, showing the capabilities of the approach to support fault diagnosis.**

I. Introduction

The growing extension of mobile networks due to the ever-increasing demands of their new users, with ever more stringent requirements, has resulted in complex and dense topologies that are becoming more and more difficult to manage. In these, mobile operators spend a large part of their OPerational EXpenditure (OPEX) each year on fixing network failures. Although management systems have mechanisms that, with or without human assistance, are capable of diagnosing the cause of such failures, the multiplicity of interactions often makes this process difficult and slow.

As a result, the information collected by the communications networks themselves was incorporated into the concept of Self Organizing Networks (SON), which has evolved from theoretical works to truly automated systems in real deployments. All the processes that networks can automatically carry out for their operation are included under the SON paradigm, among which Self Healing is in charge of diagnosing and correcting possible failures.

Alongside the development of cellular networks with 5G standards, data processing systems, Machine Learning (ML) algorithms, and the incorporation of mature positioning technologies are opening up a new horizon [1], [2]. Here, positioning of the user equipment (e.g. mobile terminals) is key for the identification of failures, their location and classification. The localization of the terminals in the network is expected to become pervasive, both outdoors as well as indoors, supported by the integration of information coming from global navigation satellite systems (GNSS) in the networks as well as the use of cellular-based precise location systems [3]. In the context of 5G, localization is expected to become ubiquitously supported by the evolution of the network architecture (more dynamic and able to integrate multiple data sources) as well as from the new radio access [1]. In 5G, this is characterized for larger bandwidths and directivity, allowing for a more precise localization fully integrated in the control plane.

The use of the obtained localization fits into the context-aware paradigm, where not only network information, but also other variables that might impact the cellular performance, such as the users distributions, are used as inputs for their management.

However, the integration of localized information in cellular management and, particularly fault diagnosis, is challenging at many levels [4]: on the data side, the information generated by different network elements may be heterogeneous and stored at various points in the network, and also the task of collecting and formatting the data can be cumbersome. Besides, the analysis process can be challenging in live systems. The faults arising at different points in the network may be related, and identifying the causal effect in large complex systems is not straightforward. Moreover, in recent years, Deep Learning (DL) mechanisms, and particularly Convolutional Neural Networks (CNNs), have evolved extensively due to the wide applicability of image and video recognition and classification in a vastly extensive set of fields like automated driving, security, and health. While DL algorithms have started to be explored in the SON literature [5], no comprehensive and exhaustive approach that makes use of image classifiers [6] for this purpose exists up to date rather than radio-frequency maps traditionally used by operators either from simulators or drive-tests.

In order to fill these gaps by exploiting the use of geo-localized traces, the present work defines a framework to take advantage of DL image classification algorithms for their inclusion in SON functions as supervised mechanisms. This is performed via the generation of the newly proposed *Network Synthetic Images* (NSIs). The capabilities of the proposed approach are demonstrated in its application to fault diagnosis based on a novel application of CNN classification, showing its potential and advantages over image-based State-of-the-Art (SoA) techniques.

In this way, the present work is organized as follows. Section II on the following page presents previous works related to image-based failure diagnosis, location-awareness and deep-learning in cellular networks. Subsequently, the proposed location-aware framework for the use of supervised

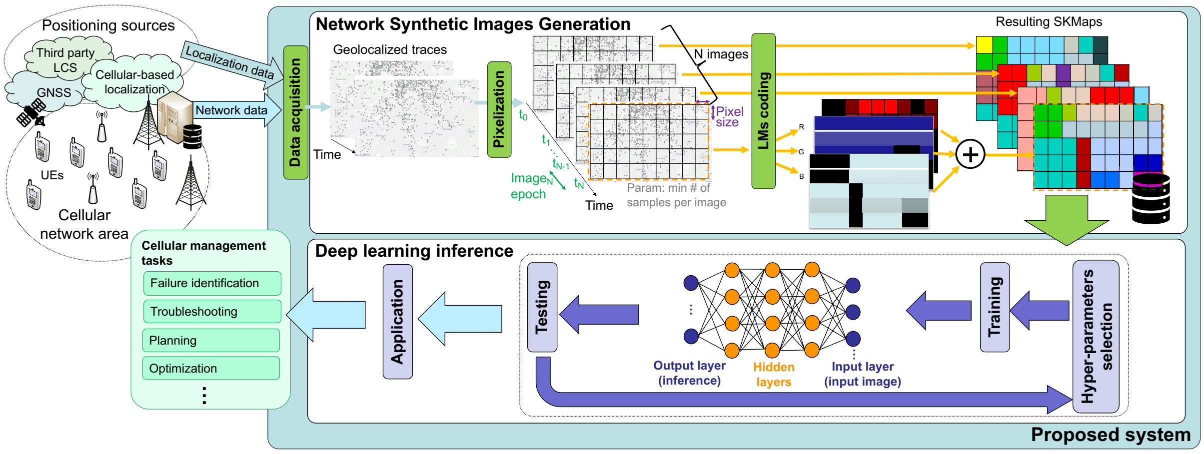

Figure 1: Proposed framework for NSI use and application.

image classification algorithms is presented in Section III, describing the details of the proposed NSIs approach as well as the rest of the functionalities of the system. From this, the proposed system is evaluated in its application to supervised Fault diagnosis in Section IV on page 4. Finally, Section V on page 5 summarizes the findings and identifies future research lines.

II. Related work

Due to the increasing complexity of new generation networks, their changing environment, and the high QoS demanding services that 5G is intended to empower, new network problems are likely to arise. Context-aware techniques for SON management solutions are gaining importance in order to solve these problems [4], [7]. The progress of computation power and the enhancement of data availability have made Artificial Intelligence (AI) algorithms attain great relevance in network management by providing network interactivity and decision-making capabilities without human intervention.

In the context of AI development, deep learning (DL) has gained much importance in recent years, surpassing the common machine learning algorithms. DL is a collection of algorithms used in machine learning, used to model high-level abstractions in data through the use of model architectures, which are composed of multiple nonlinear transformations. It is part of a large family of methods used for machine learning based on representations of data learning. In this way, DL mechanisms have seen an explosion on their development, particularly in their application to image classification.

Focusing on cellular network management however, the application of such approaches have been limited. In this area, the work in [5] provides an overview of the arising of deep learning models facing standard machine learning algorithms. This work also proposes the evaluation of a deep learning-based framework using auto-encoders for cell outage detection. The research given in [8] [9] applies deep learning to solve problems related to the non-orthogonal multiple access (NOMA) considered as a potential technique for 5G to increase spectral efficiency. [10] proposes an adaptive beam management scheme based on deep learning to solve the beam misalignment problem between sender and receiver.

Furthermore, there is a wide range of possible applications of AI to the SON paradigm. Another scope of SON is traffic prediction, which has become an indispensable part of 5G AI-assisted networks as addressed in [11] and [12].

The recent work in [13] introduces a solution based on the usage of Random Forests classifier, CNN, and neuromorphic deep learning models using labeled RSRP map images when faults are produced. The proposed solution (based on Supported Machine Vectors or SVM) distinguishes seven common faults in real networks obtaining an accuracy of less than 90%, although superior to methods such as Naive Bayes or Random Forest. Unlike the present work, the images are introduced from a planning tool and do not specify any special treatment feature.

Considering all these, up to our knowledge, no previous work have addressed the application of DL mechanisms to process geolocated traces by means of their conversion to an image-like format.

III. Proposed System for Image-based Geolocated Cellular Data Processing & Application

In this way, a general framework to overcome the existing shortcomings in the application of DL approaches for cellular management is proposed as summarized in Figure 1. Firstly, the system acquires User Equipment (UE) traces containing both network and localization data. On the former network information, such as the radio conditions and performance being experienced by the UEs is directly available as part of the management and control plane architecture of the network. This type of information is going to be generically referred as localized measurements (LMs). On the later, localization data is growingly available and integrated in the cellular network management and control planes, coming from cellular network-based localization (directly available by the operator), as well as from GNSS or additional 3rd party localization services (LCS) [14].

Once the data has been acquired, the next phase is based on the processing of this information in order to generate the

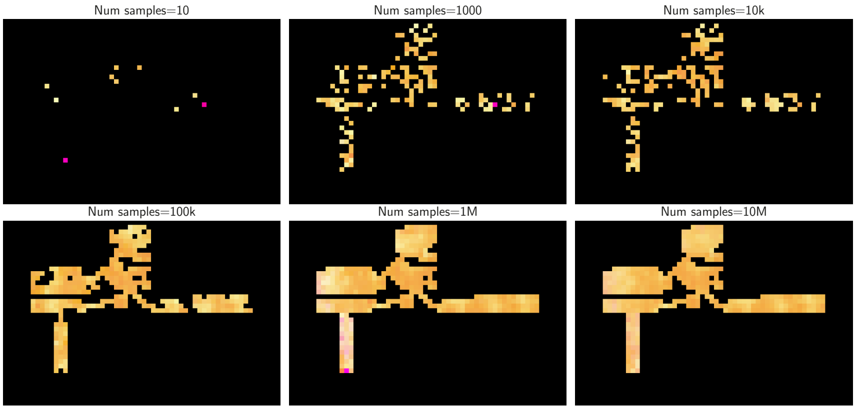

Figure 2: NSI with pixel size 5m generated with different number of samples

proposed Network Synthetic Images. These image-like data structures are the key for the application of deep learning image analysis mechanisms. Subsequently, such algorithms will allow, based on the patterns found in the NSIs, to carry out different network management tasks such as failure identification / diagnosis, detection of early error states, planning and optimization.

The next subsections describe in detail the proposed approach for both the NSIs generation and their posterior deep learning analysis, with a special focus on its application to failure diagnosis.

A. Network Synthetic Images Generation

The approach assumes that a set of positioned and timestamped traces are available and should be collected systematically over different time periods. From this, the data transformation process summarily shown in Figure 1 is applied.

First, a specific region of the space where the samples have been taken in certain time slots is identified. From this, the *pixelization* step is in charge of defining the spatial resolution of the scenario in the form of a pixel size, so the higher the resolution, the greater the number of pixels each NSI will contain. The decision on this pixel size is a key parameter in the performance of posterior stages, as it is going to be analyzed in the assessment section.

Once this segmentation has been carried out, the network data contained in the traces within the region below each pixel must be integrated by the *LM coding* step. To establish the approach, the definition of what are the constitutive elements of a digital image pixel has to be considered. In this way, multiple pixel encoding formats can be considered, like those for color, such as red/green/blue (RGB), YUV or any other. RGB encoding, being the most common allows for a straightforward integration of posterior DL image classifiers. In this way, the number of network variables (e.g. radio measurement, events, performance indicators) to be integrated can be mapped individually as either color components of each pixel. Moreover, any biased combination of them could be considered in order to better represent the network state. Such blend can be guided according to their relevance identified by applying feature engineering mechanisms [4].

The NSI will also depend on the number of network measurement samples considered, i.e., the number of LM points collected in the area for a given *acquisition time* so that, assuming a certain sampling period, the more samples an NSI contains, the longer the period of time they represent. In this respect, the number of samples to be collected during a period of time, or *image epoch*, can be aggregated in different ways. The most straightforward approach is to obtain the average of their values, although any other statistics such as their mode or percentiles are also directly applicable. Here, the availability of multiple samples for the pixel generation increases the reliability and significance of the resulting encoded value. It should also be noted that NSIs containing a larger number of samples and/or consisting of a larger number of pixels will require more computational power to be generated. The number of samples per pixel will be affected by both the image epoch and size. In this sense there is a trade-off between the number of generated NSIs and the minimum number of samples needed to build them for a fixed trace acquisition time. Fixing this minimum number of samples, the image epoch necessary to accumulate enough samples to produce an image may vary in time.

In this aspect it is relevant the high number of images that DL mechanisms may require for their training. Here, the proposed approach assumes that a set of positioned and timestamped traces are available and collected systematically over different time periods. The NSIs generated from these traces could be labeled by experts who know a priori the network states / failures. Artificial failure traces can be also constructed based on radio propagation and failure models in cases where there is not available traces data for specific failures [7]. Moreover, unsupervised approaches are also applicable for NSIs.

B. Deep-learning inference

Once a suitable number of NSIs have been obtained, they are used as input to DL image analysis mechanisms. In this sense, the choice of a specific DL algorithm is closely linked to the specific management task to be supported as well as to the proper creation of the NSIs itself, since the visual characteristics of shape, color, etc. are the ones that will determine the accuracy and efficiency of the mechanisms.

In terms of the possible DL algorithms, CNNs have enabled a great leap in quality in image classification, being able to reach accuracies of more than 90%[6]. Taking an image as input, they process it and classify it under certain categories. These are based on a process called "convolution", which consists of going through an image applying a filter and obtaining a new result image. What the neural network does is to learn features of the image, ranging from the smallest details in the first layers, to a more general view of the image in the last layers. To detect the features that make up the image and give it meaning, the CNN learns from a series of filters through a number of layers where local patterns are detected by convolution and global patterns are detected by pooling.

CNNs definition includes a series of specific hyper-parameters such as the number of layers, the activation function, epoch or batch size in addition to the traditional weights and bias, which allow a tuning that can be very refined, making it possible to achieve very high accuracy in classification algorithms.

Given all the above considerations, CNN is going to be considered as the main deep learning algorithm for image classification although, as indicated, the proposed framework is not limited to them.

IV. Evaluation

In order to validate the scope and potential of the proposed approach, the system has been implemented and tested via the system-level simulator and scenario as described in detail in [7] and from which several NSIs are shown in Figure 2. This scenario models a critical ultra-dense deployment of 12 indoor picocells covering the Málaga airport area of around 200 $\times$ 300 meters and an external macrocell. UEs, move in this following realistic pedestrian pattern with variable hotspots. Network measurements follow those in real deployments, considering UE direct measurements (RSRP, RSRQ, and SINR) reports.

Under these conditions, three possible failures have been induced (assumed to have been detected manually by the engineers after a long time): macro interference, micro interference, and power failure. Thus we have data corresponding to four different cell states: normal, power degradation, picocell interference, and macrocell interference.

For illustration, a set of NSIs has been generated using one UE radio variable (i.e., RSRP, RSRQ, SINR) per RGB color layer. Such assignment has been made by directly mapping the intensity based on the normalization of the possible values (1 byte). Three pixel sizes have been selected (1, 5, and 10 m), which, in a real environment, would depend on the accuracy of the localization method employed by the probes. As already mentioned, the acquisition time will rely directly on pixel size in order to fill most of the image. That is why, given a certain number of samples for an acquisition time, it may be insufficient for a given pixel size as, for example, 10k samples with 1 m size. A visual representation of the influence of the number of samples used in the generation of each NSI is presented in Figure 2.

The network state is being reflected in the images. However, it is challenging for the human expert to induce the network state from them since the labels have been assigned retrospective once the problem has been diagnosed without the help of these.

Therefore, in the evaluation, different combinations of pixel size in pixel edge meters (m) and total number of NPI samples (ks) to build NSIs are applied considering that their total area shall fill the space covered by the network, leading to 4 different configurations: 1m-100ksamples (ks), 5m-100 ks, 5m-5ks, and 10m-5ks. Here data merge has been performed by taking the average value of all samples that fall within each pixel.

A CNN for image recognition with four layers is adopted. Taking as input the size of the NSI, the first step performs a 7x7 convolution, then a 2x2 pooling, followed by a 3x3 convolution, and finally a 2x2 pooling to give rise to 4 possible outputs corresponding to the labeled network states.

This CNN is evaluated for the several discussed pixel size and NPI number of samples by comparing it with the Supported Vector Machine (SVM) algorithm proposed in [13] for RF Maps and considering the optimized hyperparameters.

On the one hand, the SVM baseline mechanism is assessed in a broad campaign of tests covering the different combinations of the number of samples-pixel sizes, and SVM hyperparameters C, Gamma, and kernel (lineal, polynomial,

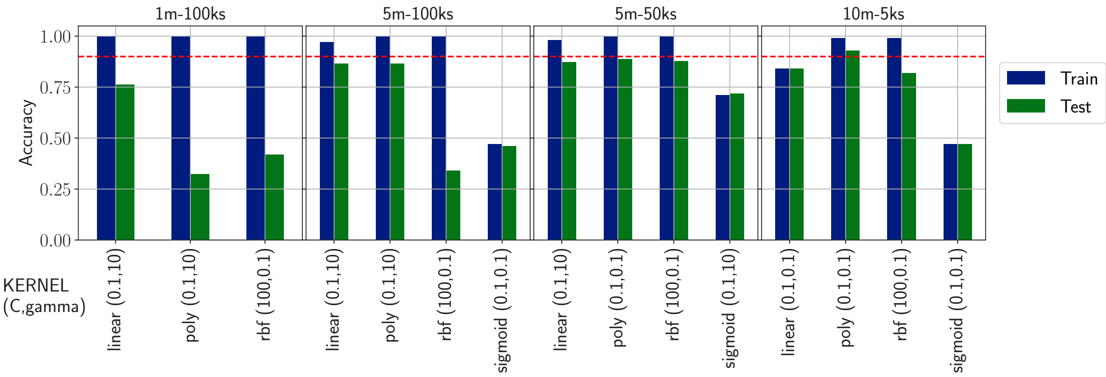

Figure 3: Performance of SVM methods (red dashed line indicates 0.9 level)

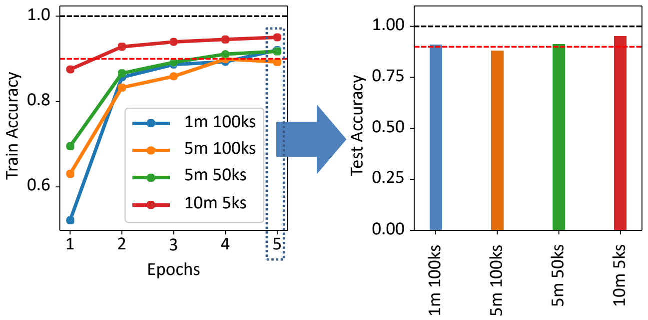

Figure 4: Performance of the proposed CNN approach.

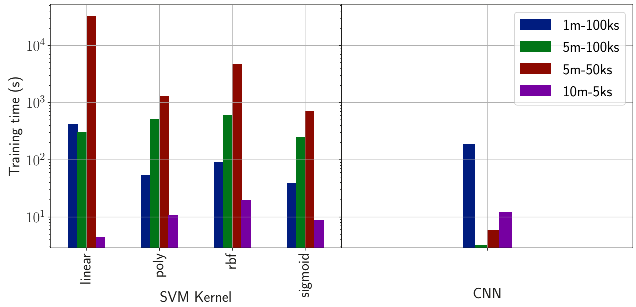

Figure 5: Training time comparison.

RBF, and Sigmoid). The accuracy values obtained for all the options are shown in Figure 3 on the preceding page for both test and training.

On the other hand, the results of the proposed CNN results are gathered in Figure 4, also for the different NSIs generation proposed options. Based on this, it can be observed how a considerably large pixel size for this scenario (10 meters) provides a testing accuracy of 95.21 % with only five epochs. Compared to any other SVM configuration results shown in Figure 3 it can be observed how a highly improved performance is achieved, being the SVM results around 80-90% and in the best case of 92.4%.

Another field where the proposed image-based CNN approach excels in respect to SVM is training time. All algorithms and configurations have been tested on an Intel Xeon processor server with eight cores with a processing speed of up to 2.4 GHz per core. As gathered in Figure 5, CNN show shortened training times in comparison to SVM, except for the 10m - 5ks configuration, where they are nearly equivalent.

V. Conclusions & Outlook

This paper has shown the opportunities and capabilities that the proposed Network Synthetic Images can provide for the management of cellular networks. Based on the defined framework for their generation based on geolocalized traces, the variables involved and their influence on the processing time have been described. Subsequently, a demonstration of its applicability in failure management has been carried out, proving that it is possible to optimize the number of samples per image and the areas to be covered to identify a network state accurately. The evaluation of the proposed framework to support CNN based classification algorithms for failure diagnosis has been shown to outperform the SVN based baseline from classic radio-frequency maps samples.

This promising approach can be used to improve many network management processes that currently require complex log review processes by experts and detect possible unnoticed problems. In this sense, future work proposes the exploration of other management techniques that can benefit from geolocated mapping, as the lack of information could also be compensated by generating adversarial networks techniques (GANs). Another line of research focused on feature engineering [15] to improve the representativeness of the NSIs, highlighting in each case the characteristics of an area to visually enhance its relevance. In addition, NSIs could be post-processed using image treatment algorithms such as filters to enhance those visual aspects that allow for a more optimal training of the ML mechanisms.

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Chapter 5

User-Centric Monitoring

5.1 Cellular Network Radio Monitoring and Management through Virtual UE Probes: A Study Case Based on Crowded Events

[70] E. Baena, S. Fortes, Ö. Alay, M. Xie, H. Lønsethagen, and R. Barco, "Cellular Network Radio Monitoring and Management through Virtual UE Probes: A Study Case Based on Crowded Events," *Sensors*, vol. 21, no. 10, p. 3404, 2021
DOI: 10.3390/s21103404

Abstract: Although log processing of network equipment is a common technique in cellular network management, several factors make said task challenging, especially during mass attendance events. The present paper assesses classic methods for cellular network measurement and acquisition, showing how the use of on-the-field user probes can provide relevant capabilities to the analysis of cellular network performance. Therefore, a framework for the deployment of this kind of system is proposed here based on the development of a new hardware virtualization platform with radio frequency capabilities. Accordingly, an analysis of the characteristics and requirements for the use of virtual probes was performed. Moreover, the impact that social events (e.g., sports matches) may have on the service provision was evaluated through a real cellular scenario. For this purpose, a long-term measurement study during crowded events (i.e., football matches) in a stadium has been conducted, and the performances of different services and operators under realistic settings has been evaluated. As a result, several considerations are presented that can be used for better management of future networks.

Chapter 6

Unlicensed Bands Provisioning

6.1 Key Quality Indicator Assessment in unlicensed bands

[71] E. Baena, S. Fortes, and R. Barco, "KQI performance evaluation of 3GPP LBT priorities for indoor unlicensed coexistence scenarios,"
DOI: 10.3390/electronics9101701

Abstract: The rapid proliferation of user devices with access to mobile broadband has been a challenge from both the operation and deployment points of view. With the incorporation of new services with high demand for bandwidth such as video in 4K, it has been deemed necessary to expand the existing capacity by including new bands, among which the unlicensed 5-GHz band is a very promising candidate. The operation of future 3GPP (Third Generation Partnership Project) mobile network standards deployments in this band implies the coexistence with other technologies such as WiFi, which is widespread. In this context, the provision of Quality of Service (QoS) or Quality of Experience (QoE) becomes an essential asset and is a challenge that has yet to be overcome. In this sense, 3GPP has proposed a traffic prioritization method based on the Listen Before Talk access parameters, defining a series of priorities. However, it does not specify how to make use of them, and even less so in potentially conflicting situations. This paper assesses the end-to-end performance of downlink unlicensed channel priorities in dense scenarios via implementing a novel simulation setup in terms of both multi-service performance and coexistence. The use of unlicensed bands is one of the most promising features envisaged to increase capacity in 5G. However, this poses multiple challenges associated with the operation when coexisting networks are present, such as WiFi.

Previous coexistence analyses have been focused on the user-plane data-related transmissions and mainly based on abstract models. Meanwhile, the effects of the shared channel signaling defined by the standards have been mostly disregarded, particularly for ultra-dense scenarios. This paper assesses how the shared data channel signaling mechanisms influence the performance of the coexisting technologies operating unlicensed bands in indoor environments. Based on this analysis, some DRS signaling modifications are envisaged to additionally enhance the service provision and fairness towards WiFi in these scenarios.

6.2 Listen Before Talk Signaling Optimization Mechanism for Unlicensed Band

[72] E. Baena, S. Fortes, and R. Barco, "Assessing the impact of DRS signaling in unlicensed indoor coexistence scenarios," *EURASIP Journal on Wireless Communications and Networking*, vol. 2020, no. 1, p. 224, 2020
DOI: 10.1186/s13638-020-01834-x

Abstract: The use of unlicensed bands is one of the most promising features envisaged to increase capacity in 5G. However, this poses multiple challenges associated with the operation when coexisting networks are present, such as WiFi. Previous coexistence analyses have been focused on the user-plane data-related transmissions and mainly based on abstract models. Meanwhile, the effects of the shared channel signaling defined by the standards have been mostly disregarded, particularly for ultra-dense scenarios. This paper assesses how the shared data channel signaling mechanisms influence the performance of the coexisting technologies operating unlicensed bands in indoor environments. Based on this analysis, some DRS signaling modifications are envisaged to additionally enhance the service provision and fairness towards WiFi in these scenarios.

Part III

Achievements

Chapter 7

Conclusions

Content

This chapter is dedicated to review the main contributions (Section 7.1) as well as the discussion and suggestion of future lines of work (Section 7.2). Finally, Section 7.3 provides a synthesis of the results derived from this thesis.

7.1 Main contributions

Throughout this thesis, several context-aware techniques in the automatic management of cellular networks have been developed to improve the efficiency in the use of resources, maximizing the performance of user services or applications and preventing their possible degradation caused by the context.

Based on these premises, an exhaustive compilation has been made of those contextual aspects that pose a challenge when it comes to integrating them into the management and operation systems of cellular networks.

Once the challenges to be faced have been specified, the main objectives that enable each of the proposed functionalities have been defined. In this way, the results obtained on the basis of each of these objectives have been presented, grouped by subject, and following the structure of this report.

The first two objectives (Obj.1, and Obj.2) are framed within the social and localization awareness of network management. They are followed by Obj.3 and Obj.4, which pursue the enablement of advanced monitoring, allowing user-centric management through on-demand monitoring of service metrics. Last but not least, Obj.5, Obj.6 and Obj.7 provide the framework for the optimal provisioning for cellular networks in unlicensed bands based on user-perceived quality of service.

The following is a summary of the contributions made according to each of these objectives separately:

- **Objective 1: To propose a method for predicting network performance in crowds based on context sources.**

  The contributions corresponding to this objective are, firstly, the design of a framework for working with data from open sources with event information. Its design has been structured in three blocks with an input of performance indicator information in the form of time series. Secondly, a novel NARX predictor that is able to predict with high accuracy solely based on historical performance and social information has been proposed. It has a flexible architecture and needs little input, so it does not involve the acquisition of other metrics beyond those currently available. It predicts up to 24 steps in advance to allow time for mitigating actions or resource allocation.

  Thus, the proposed method directly adds social awareness to the network manager and does not require substantial modifications to its operation. In this sense, it is only necessary to include a block of acquisition and preprocessing of social event sources in addition to the software-implementable functions of monitoring, filtering, and prediction.

The system has been tested using traces from a commercial network in operation located in an area close to a venue where crowds of people gather for social events. Based on this information and available APIs with details about the dates where events were held in a nearby area, the proposed predictor was implemented.

- **Objective 2: To develop a framework to enhance the use of positioned traces for network management purposes.**

  Given the increasingly ubiquitous and inexpensive access to location data, it is of interest to be able to incorporate it into automatic operation mechanisms. On the other hand, artificial intelligence developments in image processing are capable of performing recognition tasks with very high accuracy. Based on these two premises, this thesis has proposed a framework for the construction of artificial images that help to identify network states or detect patterns or precise locations of faults. The main variables that influence the construction process of such images have been described and can be optimized for a shorter processing time, algorithm training time, or for higher classification accuracy.

  Based on simulated data from an airport LTE network, the effectiveness of the framework has been tested with a supervised cellular network state detection method. The results suggest that it is possible to detect these states with classification accuracy levels above 90% without requiring high-precision localization methods.

  Although the use of localization has been postulated on several occasions as an asset for cellular network management in current deployments, it is still not fully integrated.

- **Objective 3: To propose a framework for experimental user metrics evaluation based on virtual probing**

  One of the biggest challenges in user experience management is the lack of terminal traces that include metrics of the service demanded in each case.

  In this sense, one of the most relevant contributions is the proposal of a framework for the collection of this type of traces based on virtualization and access to SDR software-defined radio technologies. The parts that need to be included in a mobile network with virtualization capabilities in order to integrate it into the operation and maintenance cycle have been described, as well as the essential mechanisms for its implementation.

Through the instantiation of virtual UE user terminal (vUE) probes, the possibility of executing either on a regular basis or on-demand various experiments involving testing the quality of a particular service is enabled. In addition to the collection of quality-of-experience metrics, simultaneous radio-level traces can be included. This facilitates cross-layer optimization and makes it possible to detect adverse effects of configurations, for example.

A comprehensive review of the applications and challenges of incorporating vUE probes into network management for advanced monitoring tasks is also provided. These include aspects ranging from fault management, planning, optimization, and implementing pilots of new standards.

- **Objective 4: To assess the service experience from the user's point of view when there are temporary crowds due to social events.**

  The concentrations of people, being social events outside the operation of cellular networks, cause degradations experienced by users who make use of services supported by these networks.

  In this sense, this thesis provides a novel field study conducted in a real scenario located in a soccer stadium with a setup that includes probes connected to several operators. In this study, the fundamentals of the framework proposed in Obj.3 are put into practice and, through the deployment of several virtualized probes, an extensive campaign of measurements of the quality perceived by users on dates where an event took place has been carried out.

  The degree of impact on multiple services when an event takes place has been tested, highlighting the factors that influence it. It has also been proven that there are substantial differences in the results obtained for each service depending on the time slot and its correlation with radio parameters.

- **Objective 5: To carry out the coding and adaptation of a full RAN stack simulator tool for realistic service assessment in unlicensed bands.**

  One of the most disruptive innovations introduced by 3GPP cellular technology standards has been the introduction of operation in unlicensed spectrum bands. This implies a series of mechanisms that, unlike those traditionally implemented by proprietary planned cellular systems, require the ability to manage random access to the medium. As it is not yet a proven technology, only few manufacturers implement this type of standard, so at the time research work was performed, there was no possibility of knowing the real operation beyond simplified simulations.

Based on the LENA module of the ns3 full stack simulator, the creation of a scenario of ultra-dense indoor coexistence of LAA technology with WiFi with the possibility of transmitting FTP and video is provided.

This adaptation allows the evaluation, including cross-layer and channel effects of the quality perceived by the users. The measurements are complemented with various IP-level metrics such as packet loss, end-to-end delay, or throughput.

- **Objective 6: To evaluate service performance in coexistence scenarios using unlicensed bands.**

  The experimental nature of cellular operation in unlicensed bands means that at the time of writing this thesis, there were no studies that evaluated the perception of the quality of service from the user's point of view.

  Based on the simulated development, the elaboration of a video streaming and FTP services performance dataset from a dense environment of coexistence with WiFi users is provided. It demonstrates that an indoor environment has fairness and performance issues depending on the load conditions.

- **Objective 7: To provide an optimized unlicensed band signaling mechanism to improve user service performance.**

  An exhaustive study of the in-band DRS signaling required for operation in unlicensed bands is provided as a final contribution. In this study, the impact of the signaling configurations on the throughput and latency perceived by the user is tested at different load levels.

  The results indicate that optimizing such a DRS configuration can have less impact on the performance of the service provided to the user since it can be dynamically modulated.

7.2 Future work

From the development of this thesis, additional research lines and applications have been identified. These include both alternative additions supported by the present work as well as further evolutions and applications of it:

- **Advanced unlicensed bands provisioning**: In terms of operation in the unlicensed spectrum, the standard has evolved towards NR-U with two modalities, non-standalone and standalone. Both alternatives must meet fairness criteria with coexisting technologies not only in sub-6GHz bands but also in the new mmWave bands. This implies that there is a gap to cover in terms of the operation of services with specific low latency requirements or that require massive use of the uplink, for example, Extended Reality (XR).

  In addition, to use as a capacity complement, opportunistic or backhaul use can also be enabled through the use of unmanned aerial vehicles (UAVs) as mobile base stations.

  Development on the recently created NR-U module in ns3[73] would be necessary to test the effect of beams management and Listen Before Talk protocols on the performance of the services according to the user load.

- **Further aspects of user-centric management**: The trend toward fully virtualized and open mobile networks deployed in different data centers (edge, far-edge, and cloud) is noteworthy [74]. Under this paradigm, access to contextual information from various sources will become more flexible, and it will be possible to implement the optimization of the user experience as a service in the form of containerized applications.

  The management of new critical URLLC, eMBB, or Time Sensitive Networking (TSN) services is also envisaged [75], especially for Industry 5.0.

- **Social and Context-Aware enhancements**: In terms of social awareness, crowds that happen in an unexpected way, as opposed to venues or social events, have recently been proposed as a use case for crowds [76].

  ML-based solutions are especially effective when the available historical information is extensive and when the number of active users varies significantly; it is proposed to explore the low fidelity of the dataset or limited computational capabilities.

The use of new localization sources is also proposed to create the network images, either from mergers of estimates from other technologies [77]. The objective is to optimize the number of data required to generate an image capable of characterizing the state of a network. The use of unsupervised algorithms capable of labeling images without the help of human experts is also envisaged.

- **Additional enabling features**: Subsequent generations of mobile technology, such as 6G, are proposed to make AI a native feature of the network by having the ability to infer and learn embedded at any point in the network [78]. Thus both the system architecture and the transmission protocols and techniques must be thoroughly reformed. In this sense, connectivity has to be managed jointly with computational resources, sensing, and data availability for training. In general, the use of AI-native is of interest [79] to integrate the three approaches presented in this thesis into a global management system ranging from domain orchestration to network deployment and operation tools as a multi-domain service. This opens up an important line of research in this direction that is just beginning to take its first steps. Conversely, in recent years, several independent alliances and forums (i.e., Telecom Infraproject [80], xRAN [81], ORAN Alliance [82]) has initiated research to accelerate this RAN transformation by increasing infrastructure virtualization together with embedded intelligence to deliver more agile services and advanced capabilities to users in what is known as Open-RAN. This model aims to decrease vendor lock-in and deployment of proprietary hardware and software by establishing open standard RF interfaces, which will help increase the operational savings already provided by virtual RAN (vRAN) and Cloud-RAN (Cloud-RAN or C-RAN). This proposal will enable the deployment of remote radio heads (RRH) and baseband units (BBU) from different vendors to build modular and scalable RAN networks. In addition to flexibility, the openness of RAN components accelerates the provision of new functions and services that can be dynamically introduced to the user. However, in managing this paradigm, today's technology faces major challenges [83]. Generic hardware still consumes far more computing resources than traditional custom hardware and therefore carries higher costs and power consumption, which means that related work is at a very immature and early stage of development.

7.3 Outcomes

The following subsections present the publications related to this thesis.

7.3.1 Journals

Publications arising from this thesis

The work carried out in this thesis has resulted in four papers published in high impact journals plus one in the process of revision, listed as follows.

Table 7.1: Journal publications.

	Publication arising from this thesis	IF	Journal Rank
I	J. Villegas, E. Baena, S. Fortes and R. Barco, "Social-Aware Forecasting for Cellular Networks Metrics" *IEEE Communications Letters* vol. 25, no. 6, pp. 1931-1934, 2021	3.553	Q2 (39/94) Telecommunications
II	Baena, E.; Fortes, S.; Muro, F.; Baena, C; and R. Barco, "A novel synthetic image-based approach for location-aware management of cellular networks," *IEEE Network*, Under review 2022	10.294	Q1 (5/94) Telecommunications
III	E.Baena, S.Fortes, O.Alay, M.Xie, H.Lønsethagen, R.Barco, "Cellular Network Radio Monitoring and Management through Virtual UE Probes: A Study Case Based on Crowded Events." *Sensors*, vol. 21.10,3404 , 2021	3.847	Q2 (95/276) Engineering, electrical & electronic
IV	E.Baena, S.Fortes and R.Barco, "KQI Performance Evaluation of 3GPP LBT Priorities for Indoor Unlicensed Coexistence Scenarios" *Electronics*, vol. 9, 1701, 2021	2.69	Q3 (139/276) Engineering, electrical & electronic
V	E.Baena, S.Fortes and R.Barco, "Assessing the impact of DRS signaling in unlicensed indoor coexistence scenarios" *EURASIP Journal on Wireless Communications and Networking*, 2020	2.455	Q3 (141/273) Engineering, electrical & electronic

Publication related to this thesis

In parallel, the author has worked jointly on research projects to which he has contributed and which have resulted in several publications in indexed journals.

Table 7.2: Journal publications related.

	Publication	IF	Journal Rank
VI	S. Fortes, J. Santoyo-Ramón, D. Palacios, E. Baena et al., "The Campus as a Smart City: University of Málaga Environmental, Learning, and Research Approaches" *Sensors, 19 (6), 1349, 2019*	3.275	Q2 (36/91) Engineering, Electrical & Electronic
VII	A. Herrera-Garcia, S. Fortes, E. Baena, J. Mendoza, C. Baena and R. Barco, "Modeling of Key Quality Indicators for End-to-End Network Management: Preparing for 5G" *IEEE Vehicular Technology Magazine*, 14 (4), 76-84, 2019	7.921	Q1 (7/90) Telecommunications
VIII	C. Baena, S. Fortes, E. Baena and R. Barco, "Estimation of Video Streaming KQIs for Radio Access Negotiation in Network Slicing Scenarios" *IEEE Communications Letters*, vol. 24 (6), pp. 1304-1307, 2020	3.436	Q2 (14/82) Telecommunications
IX	Peñaherrera-Pulla, O.S.; Baena, C.; Fortes, S.; Baena, E.; Barco,R "Measuring Key Quality Indicators in Cloud Gaming: Framework and Assessment Over Wireless Networks" *Sensors*, vol. 21, 1387, 2020	3.576	Q2 (77/266) Engineering, Electrical& Electronic
X	Fortes, S.; Baena, C.; Villegas, J; Baena, E.; Zeeshan, A.M; Barco, R "Location-Awareness for Failure Management in Cellular Networks: An Integrated Approach" *Sensors*, vol. 21, 1501, 2021	3.576	Q2 (77/266) Engineering, Electrical & Electronic
XI	Aguayo, L.; Fortes, S.; Baena, C.; Baena, E.; Barco.R, "A Multivariate Time-Series Based Approach for Quality Modeling in Wireless Networks" *Sensors*, vol. 21, 2017 , 2021	3.576	Q2 (77/266) Engineering, Electrical & Electronic
XII	R. Torres, S. Fortes, E. Baena and R. Barco, "Social-Aware Load Balancing System for Crowds in Cellular Networks" *IEEE Access*, vol. 9, pp. 107812-107823, 2021	3.367	Q2 (36/91) Telecommunications
XIII	Peñaherrera-Pulla, O.S.; Baena, C.; Fortes, S.; Baena, E.; Barco, R, "KQI assessment of VR services: A case study on 360-Video over 4G and 5G" *IEEE Transactions on Network and Service Management*, In press 2022	4.195	Q2 (47/161) Computer Science, Information Systems
XIV	F.Muro, E.Baena, S.Fortes, C.Baena and R.Barco, "Noisy Neighbour impact assessment and prevention in virtualized mobile networks " *IEEE Transactions on Network and Service Management*, In press 2022	4.195	Q2 (47/161) Computer Science, Information Systems

7.3.2 Conferences and Workshops

Conferences arising from this thesis

Several works have also been presented at national and international conferences, as shown in Table 7.3.

Table 7.3: Conferences arising from this thesis

XV	E.Baena, S. Fortes, R. Barco, “Evaluación del protocolo Listen Before Talk en el estándar 3GPP Licensed Assisted”, *XXXIII SImposium nacional de la Unión Científica Internacional de Radio, Granada*, 2018
XVI	E.Baena, S. Fortes, C.Baena, R. Barco, “Optimización de señalización en el canal común descendente para el estándar LTE-LAA”, *XXXIV SImposium nacional de la Unión Científica Internacional de Radio, Sevilla*, 2019
XVII	E.Baena, S. Fortes, R. Barco, “Impact of Unlicensed-band Listen Before Talk Priority Classes in Ultra-dense Scenarios” *COST IRACON 11th MC meeting and 11th technical meeting*, Gdansk, Poland, 2019
XVIII	E.Baena, S. Fortes, R. Barco, “DRS signaling optimization in unlicensed dense coexistence scenarios” *3rd POST IRACON Meeting*, Online, 2021

Conferences related to this thesis

Table 7.4: Conferences related

	Conferences related to this thesis
XIX	S. Fortes,E.Baena, R. Barco, “Might 5G Technologies Increase or Reduce the Digital Divide?” *IEEE Global Communications Conference (IEEE GLOBECOM)*, Abu Dhabi, UAE, 2018
XX	A. Herrera-García, S. Fortes, E. Baena, J. Mendoza, C. Baena, R. Barco, “Estimation of Service Quality Indicators in Cellular Networks’ *COST IRACON 11th MC meeting and 11th technical meeting*, Gdansk, Poland, 2019
XXI	A.Moreno-Sancho, E.Baena, S. Fortes, R. Barco, “Sonda experimental de monitorización de redes móviles para eventos”, *XXXV Simposium Nacional de la Unión Científica Internacional de Radio, Malaga*, 2020
XXII	F.Muro; E.Baena, S. Fortes, L.Mikkelsen, M.Dieudonne,J.Torrecilla, A.Sethu, R.Barco, “Evaluación del impacto del Noisy Neighbour en redes móviles virtualizadas”, *XXXVI Simposium Nacional de la Unión Científica Internacional de Radio, Vigo*, 2021

7.3.3 Related projects

This thesis was partially funded by the following projects:

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- *Horizon 2020 project LOCUS (ICT-871249) receiving funds from the European Union*
- IDADE-5G UMA18-FEDERJA-201 Programa Operativo FEDER Andalucia 2014-2020
- PENTA P18-FR-4647 Proyectos de investigación en colaboración con el tejido productivo

- SMART Incentivos a los agentes públicos del Sistema Andaluz del Conocimiento, para la realización de proyectos de I+D+i., en el ámbito del Plan Andaluz de Investigación, Desarrollo e Innovación PAIDI 2020
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Additionally, the author has participated in the following projects:

- Inteligencia Artificial para el Análisis y Monitorización de Redes de Comunicación 5G (IA2MON-5G). (Ref. UMA-CEIATECH-13, "Proyecto singular de actuaciones de transferencia del conocimiento CEI Andalucía TECH. Ecosistema innovador con inteligencia artificial para Andalucía 2025", Junta de Andalucía)
- MUSE - Massive USer Experience Assessment and Prediction for Mobile Networks. (Ref. UMA-CEIATECH-15, "Proyecto singular de actuaciones de transferencia del conocimiento CEI Andalucía TECH. Ecosistema innovador con inteligencia artificial para Andalucía 2025", Junta de Andalucía)
- 5G-SCARF - 5G Smart Communications for the AiRport of the Future (Ref. UMA-CEIATECH-17)
- Gestión integral avanzada de funciones SON (Self-Organizing Networks) para redes móviles futuras, P12-TIC-2905, Proyectos de Excelencia, Junta de Andalucía.

7.3.4 Research stays

This thesis involved a three-month stay as a visiting researcher at the Mobile Systems and Analytics (MOSAIC) department at Simula Metropolitan Center for Digital Engineering (Oslo, Norway). This stay was supervised by Dr. Özgü Alay in collaboration with the cellular network operator Telenor. The work in section 5.1 mainly reports the results achieved.

Eduardo Baena Martínez

Málaga, Spain, 2022.

Appendices

Appendix A

Assessment tools

Content

The techniques developed in this thesis have been supported by several tools: an LTE system level simulator, a full stack simulator of 3GPP operation in unlicensed band and automated data collection from real cellular networks using programmable probes.

These last two tools are described in the following subsections clearly distinguishing the developments made during the development of the thesis by the author.

A.1 LENA ns3 simulator model

System-level simulators are a fundamental tool in the development of automatic cellular network management mechanisms, as the data set available for research in real networks is still difficult to obtain and often incomplete. Even more so when dealing with situations of network failure or congestion. In these cases the data collected is usually not properly labeled and the only information available is the time stamp of the occurrence of the alarm or failure.

In this way, ns3 is a network simulation software with discrete events, developed in C++ and focused on Internet systems. It should be noted that it is free software and has a GNU GPLv2 license (GNU General Public License version 2), and it is also available to any type of public, which allows it to be used for educational and research purposes [84]. Among the functionalities implemented with this simulator is the LENA module oriented to LTE/EPC networks [85]. is aimed at manufacturers of small and large LTE cells for the development of algorithms and solutions for SON. Specifically, the LENA extension for LAA described in this work[86] has been used.

A.1.1 Author's contributions

On the indoor scenario proposed by 3GPP to evaluate coexistence with WiFi, the code has been modified to enable the priorities proposed in the document. The CDRS method shown in chapter 6 was also implemented.

Subsequently, logs have been added to capture the mobility of users and the base station to which they are connected at any given moment.

The functions in LENA have been modified so that a streaming server provided by the Evalvid module can be connected in the case of LAA. Likewise, although they were not finally included in the work, CQI and MC loggers were made.

Finally, and with the purpose of launching multiple simulations for statistical consistency, a Python script in charge of this task was automated. This script was in charge of changing the simulator configurations, launching the simulations, collecting the data from the logs and aggregating them in a consistent way.

A.2 MONROE nodes

The MONROE platform is a software environment created from an H2020 project with the same name that manages more than 300 LTE and WiFi probes (MONROE nodes) distributed across Europe. The nodes are managed remotely based on Docker software.

Dockers or containers provide an isolated environment for running applications by wrapping the software code in a complete file system containing everything needed for execution. This ensures that the software will run the same regardless of its environment. The containers share the underlying host resources, but only include what they need to run your applications. Using Dockers, multiple experiments and measurements to run on the MONROE nodes can be scheduled allowing to compare the performance of each network and explore ways to combine resources from different networks.

A.2.1 Author's contributions

As part of the eSON project, the 2nd Open Call for Experimenters, launched by the MONROE platform consortium, proposed the task of integrating two MONROE nodes to the UMA HetNet network. This task, together with the measurement campaigns launched, was carried out by the author. In addition, some improvements were made to allow simultaneous capture of control plane messages along with the experiments and to add enhanced capture capabilities.

The UMA HetNet is a heterogeneous mobile communications test network, consisting of a set of twelve 4G/LTE and WiFi mobile communications picocells and a network core, an integrated WiFi network, a network management platform and specific terminals for the analysis and capture of traces.

To automate the execution of experiments as well as the analysis of their results, SSH (Secure Shell) connections by one of the nodes interfaces has been enabled, allowing the establishment of connections from different computers to the nodes. These connections can be used to send commands to the nodes to perform a certain experiment and to obtain the measurements made by the node during the experiments execution. On the other hand, if it is necessary to modify the UMAHetNet network configuration parameters between the different experiments, the computer connected to the node must also be connected to the picocell network. Thus, by using a REST API, it has been possible to perform successive experiments with different network configuration parameters.

Several tools have been added to MONROE nodes to collect measures that would allow for a deeper understanding of the crosslayer aspects of QoE.

Firstly, and based on a previous tool RMBT, this experiment measures the maximum available bandwidth over a given Internet connection, in our case LTE based. This is done by launching multiple TCP threads in parallel for a preset amount of time (5 seconds by default). The test is composed in 7 phases:

- Phase 1- Initialization: It tries to connect to the Control Server on the TCP port 443 using TLS
- Phase 2- Downlink pre-test: ensures that the Internet connection is in an active state, e.g. that dedicated radio resources are available (RRC_CONNECTED state). This makes the tests results independent of the preceding usage of the access and thus leads to reproducible test results. In addition, the pre-test gives a coarse estimate of the bandwidth. If the estimate for the available bandwidth is very low, the test continues with 1 connection instead of the preset configured number.

- Phase 3- Latency test: the client sends a number of pings in short intervals to the Nettest Server to test the latency of the link
- Phase 4- Downlink RMBT: the TCP connections previously opened start sending packets to occupy the available bandwidth
- Phase 5- Uplink pre-test: similar process to phase 2 for uplink.
- Phase 6- Uplink RMBT: similar process to phase 3 for uplink
- Phase 7- Finalization: release of all the connections and data gathering.

The data collected in each of these phases are summarized in several files in json format (see Table A.1) that are saved once all the phases described above are successfully completed.

Table A.1: Files generated by Nettest and the information they contain.

Filename	Information
NodeId_MONROE.EXP.NETTEST__.json	Basic experiment info, timestamps and configuration
NodeId_MONROE.EXP.NETTEST_FLOWS.json	Relative time series of transmission flow (bytes received in time) of pretests and tests
NodeId_MONROE.EXP.NETTEST_STATS.json	Relative time series of TCP flow each 100 ms
NodeId_MONROE.EXP.NETTEST_TRACEROUTE.json	Traces the route of IP packets to the server. Such route can involve many different systems along the way referred to as hops

Secondly, PDSCH channel sniffing capabilities were added to UMA nodes using the system proposed in MONROE SOPHIA[87]. Based on a low-cost RF front-end hardware from Lime Microsystems[88] it collects samples every 3 seconds without registering to a network with the following information:

1. Side_info with radio link information, cell load, number of users and MCS of the cell
2. Total Cell Throughput (Mbps): containing Total cell Downlink and Total cell Uplink
3. Users Traffic (Mbytes): containing values per user

Third, the Mobile Insight tool developed by UCLA [89] was enabled in the MONROE nodes. This software allows the tracing of the entire user control plane (PHY, MAC, RLC, RRM, NAS layers) while performing any experiment. In this way it is possible to analyze how resources are dynamically allocated while watching a YouTube video for example.

Appendix B

Summary (Spanish)

Content

Se presenta un resumen de esta tesis, describiéndose los antecedentes, los desarrollos llevados a cabo, las conclusiones obtenidas y las aportaciones realizadas.

B.1 Introducción

B.1.1 Antecedentes y justificación

El auge de la digitalización de las sociedades modernas, impulsado especialmente por la pandemia de la COVID-19, ha acelerado la proliferación de dispositivos capaces de conectarse a las redes celulares. Así pues, hoy día no es raro encontrar un ordenador de a bordo en un coche, unas gafas de realidad virtual o un diminuto sensor con conectividad móvil. Como consecuencia, la oferta de servicios ha ido aumentando y diversificándose llegando a ser muy heterogénea en cuanto a la demanda de requisitos de red. Según estudios recientes [1], toda esta aceleración de la tendencia a la adopción masiva de la tecnología hace que la previsión de la demanda de tráfico para 2026 de los usuarios de redes celulares alcance 1,5M de petabytes, lo que equivale a 214M de horas de vídeo con calidad 4K. De este modo, a medida que aumenta el número de elementos de red, también lo hace la complejidad de su gestión y su funcionamiento. Las operadoras de redes móviles, por lo tanto, se enfrentan a un reto cada vez mayor para contener tanto los gastos de capital (CAPEX), como los gastos operativos (OPEX).

Si bien la tecnología 4G o Long Term Evolution [2] ha contribuido en gran medida a simplificar la arquitectura de los sistemas celulares, los despliegues actuales siguen estando rígidamente definidos y tienen funcionalidades estáticas. En este sentido, la planificación y la gestión se llevan a cabo de forma manual o semi-automatizada, lo que requiere estructuras de apoyo que necesitan mucha mano de obra.

Por este motivo, previa aparición del 4G, se introdujo el concepto de Redes Autoorganizadas [90] (SON, Self-Organizing Networks) basado en los requisitos definidos por las operadoras en la Next Generation Mobile Networks Alliance (NGMN) [3]. El objetivo de esta innovación era dotar a las redes celulares de la inteligencia y la adaptabilidad que permitieran una gestión autónoma. En este sentido, se habilitan mejoras en la capacidad, cobertura, eficiencia espectral y la resiliencia de la red, reduciendo los costes de Operación, Administración y Mantenimiento (OAM) [4, 5].

Desde un punto de vista académico, se han venido proponiendo múltiples desarrollos de algoritmos SON así como productos comerciales que se ofrecen como complemento para la red de acceso radio. Sin embargo, a pesar de su rápida evolución hacia el estándar 5G como Next Generation SON (NG-SON) [7], todavía hay muchos aspectos en su implementación que provocan serios inconvenientes y que son claramente mejorables. Algunos de los más reseñables son los siguientes:

- Los sistemas actuales de gestión de redes celulares operan en la mayoría de las ocasiones en base a métricas de red clásicas como el Throughput, llamadas caídas o nivel de cobertura, sin embargo, no se tiene en cuenta la calidad de experiencia (QoE) que tiene el usuario de un servicio o aplicación soportada por la conectividad de la red móvil.

- En la mayoría de los casos, los sistemas de gestión se basan en un principio reactivo, sin capacidad para anticiparse a las posibles fluctuaciones de la demanda o posibles problemas asociados a una incidencia que pueda producirse en el futuro [91].

- En entornos muy dinámicos, como son los escenarios de interior (por ejemplo, metro, centros comerciales), es muy difícil dar continuidad a la calidad ofrecida a los usuarios, siendo éste uno de los puntos débiles de la tecnología móvil actual.

Llegados a este punto, el vertiginoso avance de las Tecnologías de la Información y las Comunicaciones (TIC) han puesto a disposición del mercado una serie de herramientas que pueden actuar como potenciadores de las Redes Autoorganizadas cubriendo algunos de los puntos mencionados anteriormente.

En primer lugar, cabe destacar la actual accesibilidad y facilidad de uso de la Inteligencia Artificial (IA) con una plétora de librerías, algoritmos, bases de datos, APIs, etc. [11]. Dado el coste decreciente de los recursos de almacenamiento y computación junto con la disponibilidad de datos para el entrenamiento basado en los principios del aprendizaje automático (ML), los algoritmos de IA se han vuelto cada vez más potentes. Técnicas como el aprendizaje profundo [12, 13, 14, 15] y las Redes Adversariales Generativas [16] han permitido su aplicación en casi cualquier campo, incluyendo la gestión de redes [7].

En segundo lugar, la transformación de los equipos tradicionales de hardware que realizan las distintas funciones de red (conmutación, enrutamiento, cortafuegos, etc.) en máquinas virtuales basadas en software que se ejecutan en máquinas de propósito general (servidores) en un paradigma conocido como Network Function Virtualization (NFV). Estas funciones pueden ser orquestadas y gestionadas a través de redes definidas por software (SDN) [17], logrando un alto grado de versatilidad en comparación con sus predecesores.

En tercer lugar, el acceso a los datos a nivel de usuario, que tradicionalmente se ha realizado a través de campañas de medición conocidas como Drive Test (DT) [18], resulta muy costoso e ineficiente. Estas recopilaciones no reflejan la evolución temporal del funcionamiento de la red (cambio de parámetros, movilidad de los usuarios, condiciones ambientales...), aunque se han introducido mejoras como el Drive Test de minimización (MDT) [19] para hacerlo más accesible.

Además, los datos de localización han sido hasta ahora difíciles de obtener y de clasificar por parte de los operadores, pero ahora pueden obtenerse de forma muy económica y flexible sin intervención del usuario [20, 21, 22, 23].

Teniendo en cuenta la disponibilidad cada vez más flexible y económica de estos habilitadores y aprovechando los recursos disponibles, se pueden prever algunos desarrollos: por un lado, se puede aplicar del Machine Learning (ML) se anticipa a los posibles problemas derivados del contexto que puedan surgir dada la disponibilidad masiva de datos utilizando técnicas de predicción multifactoriales y, por otro lado, la monitorización automática de la QoE [24] puede emplearse con objeto de optimizar el rendimiento de las aplicaciones de usuario en bandas tanto licenciadas como no licenciadas

B.1.2 Objetivos

En esta tesis se proponen novedosas estrategias para hacer frente a la degradación del servicio producida por el contexto en las redes celulares desde el punto de vista de la gestión automática de la red. En concreto, tal y como se muestra en la Figura B.1, se propone abordar el problema desde tres enfoques que incluyen varios escenarios posibles.

En una primera fase, es necesario pasar de una gestión principalmente reactiva a una estrategia operativa proactiva. Este cambio es posible gracias a la madurez de los sistemas de procesamiento de Big Data potenciados por la Inteligencia Artificial y al progresivo abaratamiento de las tecnologías de procesamiento y almacenamiento de la información. De este modo, se pueden predecir con cierta fiabilidad las degradaciones del servicio en situaciones derivadas de la actividad social de los usuarios, como las concentraciones de personas. (Objetivo 1) (Objetivo 2)

Paralelamente, para garantizar la calidad de la experiencia del usuario final (QoE) y el rendimiento de la red, se requieren soluciones avanzadas de monitorización con capacidades fiables de recogida de datos en plano de usuario. Hasta ahora la incorporación de dicha información a la gestión de red ha supuesto un obstáculo razón por la cual existen numerosas situaciones no detectadas de degradación del servicio. (Objetivo 3)(Objetivo 4)

Por otra parte, dado que la capacidad de la red tiene que aumentar continuamente debido al constante crecimiento de la demanda de tráfico y la aparición de nuevos servicios, se hace necesaria una extensión de la cobertura. Sobre todo en entornos interiores, donde la macrocobertura no es suficiente para satisfacer las necesidades de capacidad, este aspecto debe ser solucionado. En este contexto, el uso de bandas de frecuencia no licenciadas es una estrategia prometedora, aunque no exenta de dificultades y riesgos, ya que la omnipresente tecnología WiFi se encuentra desplegada haciendo uso de estas bandas. (Objetivo 5) (Objetivo 6) (Objetivo 7)

De este modo, los principales objetivos se pueden resumir a continuación:

Objetivo 1: Método de predicción del rendimiento de la red en multitudes basado en fuentes de contexto. Al añadir a los sistemas actuales de gestión de redes la capacidad de integrar información procedente de fuentes contextuales abiertas (como calendarios de eventos sociales en línea, redes sociales, bases de datos en línea y otras), se pueden establecer patrones de comportamiento de la red causados por la concentración de usuarios en una zona. De este modo, apoyándose en mecanismos de previsión, la red es capaz de prevenir una posible congestión que provoque una degradación repentina durante el tiempo que dure la concentración de personas.

Objetivo 2: Definición de un marco de trabajo para mejorar el uso de trazas localizadas con fines de gestión de la red. La creciente disponibilidad de datos de posicionamiento añade valor a la información asociada a los datos de gestión recogidos por la red celular. Sin embargo, es necesario adaptar los sistemas actuales para que el tratamiento de esta información represente una ventaja que conduzca a un mejor rendimiento.

Objetivo 3: Marco de trabajo y evaluación experimental de las trazas de usuario basadas en el sondas virtualizadas. Otra fuente de información que es claramente mucho más accesible son los datos sobre la calidad de la experiencia del usuario. Esto se debe a que, a diferencia de las infraestructuras de red basadas en hardware específico, los sistemas de virtualización permiten instanciar terminales virtuales sin necesidad de invadir la privacidad del usuario.

Objetivo 4: Análisis experimental y percepción de la experiencia de rendimiento del servicio en aglomeraciones. La falta de percepción por parte de los sistemas de gestión de la red de la calidad del servicio con independencia de los indicadores de red es actualmente uno de los hándicaps que impiden la aplicación del principio "centrado en el usuario". Como complemento a los sistemas de previsión de aglomeraciones, se propone la determinación del impacto sobre la QoE en este tipo de escenarios.

Objetivo 5: Codificación y adaptación de la herramienta de simulación full-stack de red acceso radio para una evaluación realista de servicios en banda lo licenciada. Dado que el uso de las bandas sin licencia está sujeto a la regulación de los organismos de gestión del espectro, no existen dispositivos certificados capaces de operar en estas bandas. Para permitir la operación, es necesario contar con una herramienta que proporcione datos lo más realistas posibles de cómo sería un despliegue funcional.

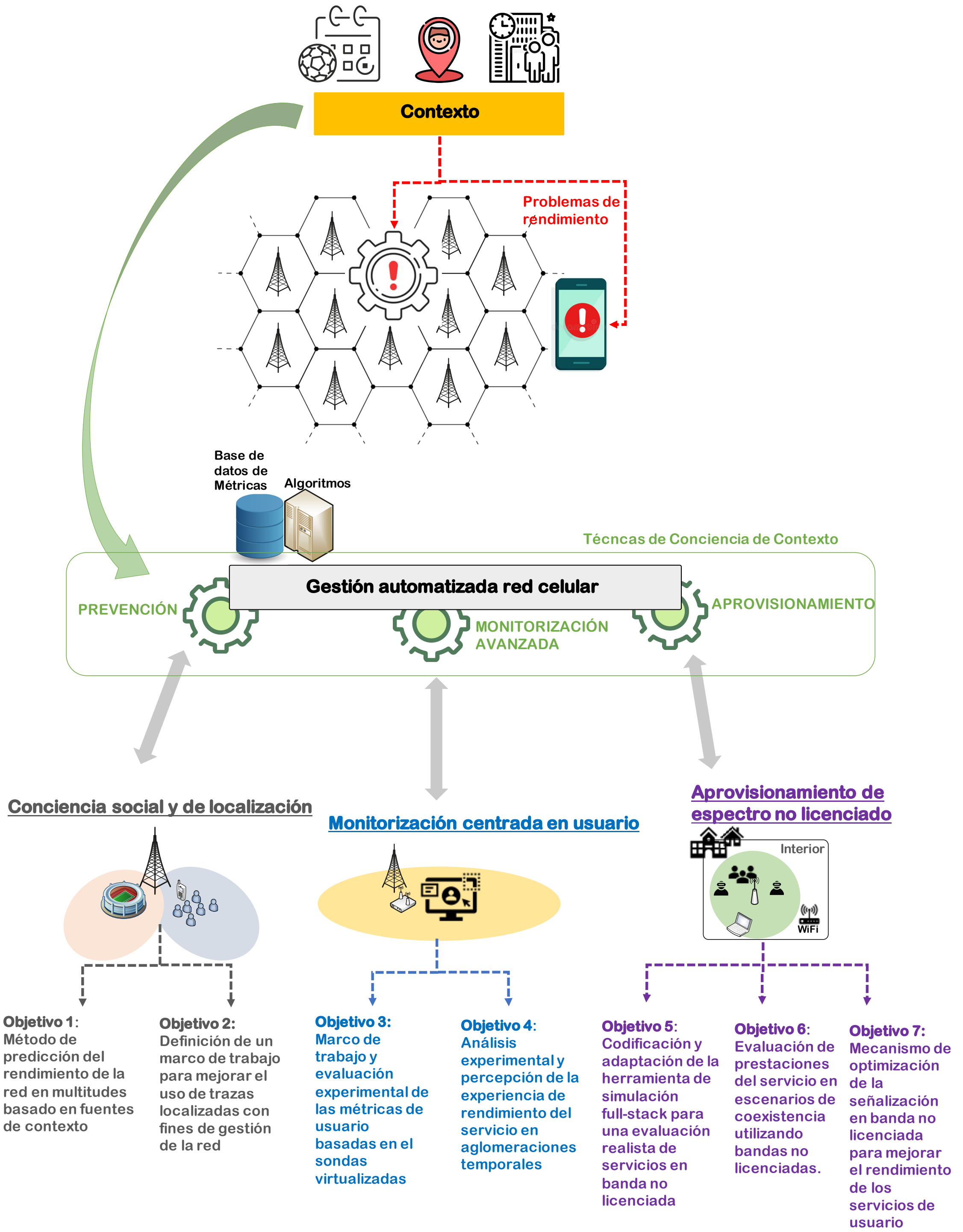

Figure B.1: Esquema conceptual de los objetivos abordados en la tesis.

Objetivo 6: Evaluación del rendimiento del servicio en escenarios de coexistencia utilizando bandas no licenciadas. Al igual que con la presencia de multitudes, otro escenario clave en el que es más probable que se produzca una degradación del servicio es el entorno de interiores. Al coexistir varias tecnologías, resulta crucial establecer los límites donde el uso del espectro sin licencia resulta ventajoso.

Objetivo 7: Mecanismo de optimización de la señalización en banda no licenciada para mejorar el rendimiento de los servicios de usuario. Una vez determinado el impacto en el servicio de las tecnologías celulares coexistiendo en la banda no licenciada, se requieren mecanismos de operación de la red centrados en el usuario para mejorar automáticamente la QoE.

B.2 Descripción de los resultados

Los resultados derivados del trabajo en esta tesis son los que se incluyen en la parte II, que se ha estructurado en tres capítulos que corresponden con cada uno de los mecanismos de conciencia de contexto propuestos para la gestión automática de redes celulares:

En el capítulo 4 se presenta un artículo que propone un método novedoso de predicción de eventos sociales basado en las métricas de la red mediante redes neuronales. En segundo lugar, se incluye otra publicación que propone un marco para la incorporación del posicionamiento en las trazas de los usuarios para formar imágenes del estado de la red a partir de las cuales realizar diagnósticos automáticos.

El capítulo 5 contiene la publicación en la que se presenta un marco de trabajo para la toma de datos de usuarios mediante sondas virtualizadas en entornos de alta concentración de personas en eventos. Asimismo, en dicho trabajo se incluye el análisis del impacto de los eventos mediante una amplia campaña de medición de series temporales.

El capítulo 6 incluye publicaciones relacionadas con la gestión de bandas no licenciadas en entornos de interior. Por un lado, se realiza una evaluación de cómo afectan los entornos interiores ultradensos en coexistencia con WiFi al servicio percibido por el usuario, y por otro lado, se propone una optimización de la señalización del protocolo Listen Before Talk propuesto por 3GPP.

A continuación, tal y como se resume en la Figura B.2, se reseña brevemente el contenido de cada uno de los trabajos.

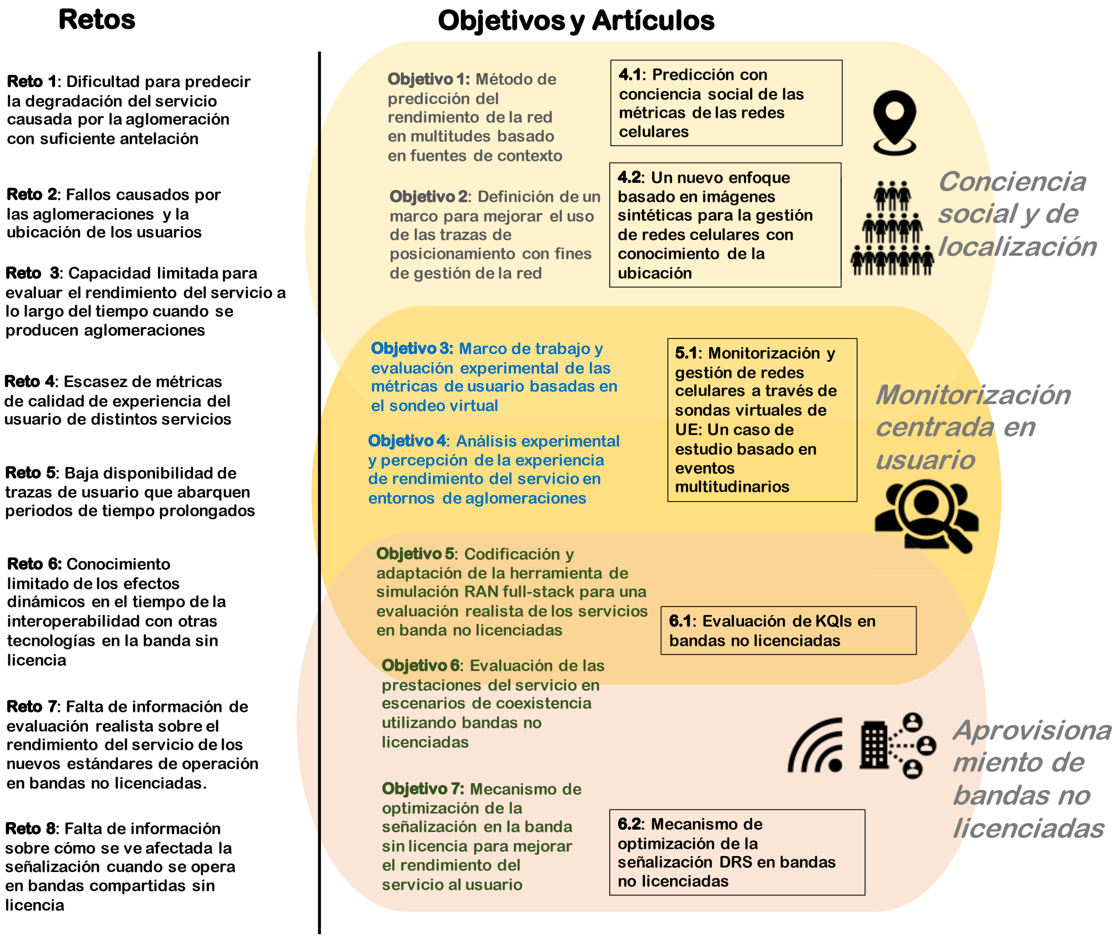

Figure B.2: Retos, Objetivos y Resultados.

B.2.1 Predicción con conciencia social de las métricas de las redes celulares

Para adquirir una verdadera conciencia de contexto social, las redes deben de incorporar información, desde fuera de la propia de la red, que permita determinar el tipo de movilidad y patrones de concentraciones de usuarios. En este sentido, cuanto más capacidad tenga una red celular de anticiparse a este tipo de eventos con un fuerte impacto en su operativa, mejor se podrán planificar y administrarse.

En el artículo presentado en la sección 4.1 se hace uso de los recursos que actualmente se encuentran disponibles como las fuentes abiertas de eventos y complementándolas a la información que recogen los operadores en forma de indicadores clave de rendimiento o KPIs. En él se propone un método que permite relacionar los impactos sobre la operativa de red con las concentraciones planificadas de personas producidas en los eventos. Por un lado, se predice el nivel de impacto que tendrán los KPIs seleccionados y por otro permite anticipar con mucha antelación dichas degradaciones. Esto se alinea con el Objetivo 2. Para ello, se adopta un novedoso enfoque de modelos exógenos autorregresivos no lineales apilados (NARX), definidos específicamente para permitir el uso de la información de los eventos sociales para mejorar la previsión de las métricas.

Posteriormente se presenta un novedoso sistema construido para soportar estos mecanismos, incluyendo una descripción detallada de sus funciones y variables. Además, se establece la metodología para la estimación de sus hiperparámetros, el entrenamiento y la aplicación de la previsión. Las predicciones proporcionadas por el sistema se han evaluado metodológicamente utilizando datos de una red celular real y se comparan con un enfoque sin conciencia de contexto social. El rendimiento del método arroja unos resultados prometedores para su aplicación.

B.2.2 Un nuevo enfoque basado en imágenes sintéticas para la gestión de redes celulares con conciencia de localización

En el capítulo 4 se introduce el enfoque dirigido a habilitar una conciencia de contexto social que permita a las redes celulares ajustar sus recursos de manera eficiente en base al uso derivado de este comportamiento. Algunas de las técnicas habilitadoras que se encuentran en fase madura del desarrollo son aquellas que permiten determinar la posición de los usuarios. No obstante, si bien existen algunas propuestas en la literatura sobre el uso de trazas de red posicionadas en la gestión automática de la red, su procesado avanzado puede ofrecer muchas más ventajas.

En este sentido los mapas de radiofrecuencia y rendimiento de red obtenidos en los DT resultan insuficientes ya que sólo reflejan un estado muy específico de la red en un momento determinado. Por otro lado, la gestión de trazas en forma de series temporales resulta extremadamente compleja a la hora de analizar patrones.

Se propone en esta publicación (sección 4.2) establecer un marco de trabajo que permita explotar la información contenida en dichas trazas posicionadas en tareas donde la gestión automática pueda ser capaz de detectar fallos inadvertidos o interacciones complejas (Objetivo 1).

Para conseguirlo se establece un método que permite transformar las trazas en imágenes sintéticas que reflejen el estado de red (NSI) destacando aquellos elementos que sean determinantes para una determinada tarea. La construcción de dichas imágenes ofrece flexibilidad para determinar la precisión de localización necesaria y la periodicidad en la toma de muestras, además de otros parámetros de relevancia. Una vez creadas, las imágenes sintéticas de red o NSI aprovechan la potencia de los algoritmos Deep Learning de clasificación de imágenes para determinar situaciones problemáticas que hayan sido etiquetadas de forma supervisada. De este modo se muestra un ejemplo de aplicación de diagnosis automática en base al marco de trabajo basado en NSI.

La metodología empleada es la simulación de un entorno aeroportuario real donde se emplazan varias estaciones de interior LTE y donde se tiene conocimiento de la localización de cada usuario. Los resultados muestran que el enfoque supera la precisión alcanzada por los métodos basados en mapas de radiofrecuencia.

B.2.3 Monitorización y gestión de redes celulares a través de sondas virtuales de UE: Un caso de estudio basado en eventos multitudinarios

Como ya se ha comentado previamente, de acuerdo con la experiencia de las operadoras los eventos multitudinarios producen un importante impacto sobre la red celular. Aunque dicho impacto resulte significativo desde el punto de vista de la gestión basada en indicadores KPI, donde realmente se deja notar dicho efecto es en la percepción de los servicios de los usuarios.

Es en este punto donde la gestión de la red debería incorporar métricas objetivas QoE en base a las cuales realizar la toma de decisiones. Este enfoque de la monitorización avanzada centrada en usuario (User-Centric) es el que se propone habilitar en el artículo en la sección 5.1 de acuerdo al Objetivo 3.

Partiendo de la madurez que las tecnologías de virtualización SDN, SDR y NFV están alcanzando, se propone un método no-invasivo de incorporación de QoE basado en sondas virtualizadas. Mediante campañas programadas de recogida de datos a partir de ejecución de diversas aplicaciones en las sondas (FTP, Video, Test de velocidad) se pretende medir objetivamente la percepción del usuario.

Con objeto de comprobar la viabilidad del marco de obtención automática de datos de usuario a la red celular se lleva a cabo un despliegue de dos sondas virtualizadas en el estadio de Trondheim (Noruega). Posteriormente se lleva a cabo una extensa campaña de medidas los días en los que se celebra un evento multitudinario cumpliendo con el Objetivo 4.

Se verifica experimentalmente el comportamiento en términos de QoE que tiene un evento pudiendo apreciarse diferencias dependiendo de la red de la operadora, el servicio y el momento en que se mide (antes, durante o después del evento). Dicha información contribuye por tanto a establecer líneas base para prevenir futuras degradaciones de servicio. Así pues, se resumen en el artículo las implicaciones que una recogida sistemática de este tipo de datos tendría y las áreas donde podrían incluirse en términos de gestión automática de redes celulares.

B.2.4 Evaluación de KQIs en bandas no licenciadas

El tradicional uso privativo de las bandas de frecuencia, propio de las tecnologías celulares, hace que resulte un recurso extremadamente escaso. Especialmente en situaciones donde existe concentración de usuarios y donde los requisitos de las aplicaciones son elevados, resulta imperativa una mayor disponibilidad espectral. Así pues, el uso de bandas no licenciadas se postula como una de las alternativas más plausibles para incorporar capacidad, de forma dinámica, en las redes celulares.

En el artículo de la sección 6.1 se lleva a cabo una evaluación realista en el enfoque que hace uso de las bandas no licenciadas. En primer lugar, acorde con el Objetivo 5, se emplea una herramienta de simulación full-stack que permita extraer resultados realistas y se adapta para simular un escenario donde el uso de bandas no licenciadas permite evitar una degradación del servicio en términos de QoE. Posteriormente se lleva a cabo una evaluación de las posibilidades que ofrece el protocolo LBT en coexistencia con WiFi en servicios como FTP y video streaming de acuerdo con el Objetivo 6.

Se recrea un escenario de interior ultradenso donde se combinan tráficos de FTP y videostreaming. Asimismo, la banda no licenciada únicamente emplea el canal compartido descendente apoyado en el canal licenciado en el ascendente. Siguiendo las indicaciones del estándar 3GPP se han probado las configuraciones de los parámetros del protocolo LBT comparando la QoE y la justicia ("fairness") con respecto a WiFi. En base a las simulaciones se concluye que con los parámetros marcados por el estándar existen opciones que resultan injustas con respecto a WiFi y que existen configuraciones preferentes para la mejora del rendimiento de ambos servicios. Esto deja paso a posibles optimizaciones automáticas en tiempo real en base a las condiciones del entorno.

B.2.5 Mecanismo de optimización de la señalización DRS en bandas no licenciadas

De manera complementaria al artículo de la sección 6.1, y englobado en el capítulo 6 que habilita el enfoque centrado en el uso de bandas no licenciadas, en el trabajo presentado en la sección 6.2 se propone un mecanismo de optimización de la señalización tal y como se marca en el Objetivo 7.

En éste se analiza el papel que tiene el tipo de señalización DRS que se emite en el canal compartido no licenciado. Bajo diversas condiciones de carga tanto de usuarios como de estaciones base y, en coexistencia con WiFi, se lleva a cabo la evaluación del impacto de dicha señalización sobre el rendimiento del servicio. Como resultado se ha identificado que la presencia de dicha señalización perjudica la justicia con respecto a WiFi y que la supresión de la misma implica una degradación de servicio. A continuación se propone un mecanismo alternativo de compensación CDRS que mejora el rendimiento en un 10% incrementando la justicia en un 25%.

B.3 Conclusiones

A lo largo de esta tesis se han desarrollado tres nuevos enfoques de la conciencia de contexto para la gestión automática de redes celulares mejorando la eficiencia en el uso de los recursos, maximizando el rendimiento de los servicios o aplicaciones de los usuarios y evitando su posible degradación en determinadas situaciones contextuales.

Partiendo de estas premisas, se ha realizado una recopilación exhaustiva de aquellos aspectos del contexto que suponen un reto a la hora de integrarlos en los sistemas de gestión y explotación de las redes celulares.

Una vez especificados los retos a los que hay que enfrentarse, se han definido los principales objetivos que permiten cada una de las funcionalidades propuestas. De este modo, los resultados obtenidos en base a cada uno de estos objetivos se han presentado agrupados por temas y siguiendo la estructura de este informe.

Los dos primeros (Obj.1)(Obj.2) se enmarcan dentro de la conciencia social y de localización de la gestión de la red. Les siguen los Obj.3 y Obj.4 que persiguen la habilitación de la gestión centrada en el usuario a través de la monitorización avanzada bajo demanda de las métricas de servicio. Por último, los Obj.5. Obj.6 y Obj.7 proporcionan el marco para el aprovisionamiento óptimo de las redes celulares en bandas sin licencia en función de la calidad percibida de los servicios del usuario.

A continuación se resumen las aportaciones realizadas en función de cada uno de estos objetivos por separado:

- **Objetivo 1: Proponer un método de predicción del rendimiento de la red en concentraciones de personas basado en fuentes de contexto.**

  Las aportaciones correspondientes a este objetivo son, en primer lugar el diseño de un framework para trabajar con datos de fuentes abiertas con información de eventos. Su diseño se ha estructurado en tres bloques con una entrada de información de indicadores de rendimiento en forma de series temporales. En segundo lugar se ha propuesto un novedoso predictor NARX que es capaz de predecir con alta precisión únicamente en base a información histórica de rendimiento y social. Tiene una arquitectura flexible y necesita pocas entradas, por lo que no implica la adquisición de otras métricas más allá de las disponibles actualmente. Predice con hasta 24 pasos de antelación para dar tiempo a realizar acciones de mitigación o asignación de recursos.

  Así, el método propuesto añade conciencia social al gestor de la red directamente y no requiere modificaciones sustanciales en su funcionamiento. En este sentido, sólo es necesario incluir un bloque de adquisición y preprocesamiento de fuentes de eventos sociales además de las funciones implementables por software de monitorización, filtrado y predicción.

  El sistema se ha probado utilizando trazas de una red comercial en funcionamiento situada en un lugar cercano a un recinto donde se reúnen multitudes de personas para celebrar eventos sociales. A partir de esta información y de las APIs disponibles con información sobre las fechas en las que se celebran eventos en una zona cercana, se han llevado a cabo las implementaciones del predictor propuesto.

- **Objetivo 2: Desarrollar un marco de trabajo para mejorar el uso de las trazas posicionadas con fines de gestión de la red.**

  Dado el acceso cada vez más ubicuo y barato a los datos de localización, resulta interesante poder incorporarlos a los mecanismos de operación automática. Por otro lado, los desarrollos de inteligencia artificial en el procesamiento de imágenes son capaces de realizar tareas de reconocimiento con una precisión muy elevada. Partiendo de estas dos premisas, en esta tesis se ha propuesto un marco para la construcción de imágenes artificiales que ayuden a identificar estados de la red o a detectar patrones o localizaciones precisas de averías. Se han descrito las principales variables que influyen en el proceso de construcción de dichas imágenes y que pueden ser optimizadas para reducir el tiempo de procesamiento, el tiempo de entrenamiento de los algoritmos o para conseguir una mayor precisión de los mismos.

  A partir de datos simulados de una red LTE de un aeropuerto, se ha probado la eficacia del marco con un método de detección supervisada del estado de la red celular. Los resultados obtenidos sugieren que es posible detectar estos estados con tasas de precisión superiores al 90% sin necesidad de métodos de localización muy precisos.

  Aunque el uso de la localización se ha postulado en varias ocasiones como una ventaja para la gestión de la red celular en los despliegues actuales, todavía no está integrada.

- **Objetivo 3: Proponer un marco para la evaluación experimental de métricas de usuario basado en el sondeo virtual.**

  Uno de los mayores retos en la gestión de la experiencia de usuario es la falta de trazas de los terminales UE que incluyan métricas del servicio demandado en cada caso.

  En este sentido, una de las aportaciones más relevantes es la propuesta de un marco para la recogida de este tipo de trazas basado en la virtualización y el acceso a tecnologías de radio definida por software SDR. Se han descrito las partes que deben incluirse en una red móvil con capacidad de virtualización para integrarla en el ciclo de operación y mantenimiento, así como los mecanismos esenciales para su implementación.

  A través de la instanciación de sondas de terminal de usuario UE virtual (vUE), se habilita la posibilidad de ejecutar, ya sea de forma periódica o bajo demanda, diversos experimentos que implican la comprobación de la calidad de un determinado servicio. Además de la recopilación de métricas de calidad de la experiencia, se pueden incluir trazas simultáneas a nivel de radio.

Estos datos facilitan la optimización entre capas y permiten detectar, por ejemplo, los efectos adversos de las configuraciones.

También se ofrece una revisión exhaustiva de las aplicaciones y los retos de la incorporación de sondas vUE en la gestión de redes para tareas de monitorización avanzadas. Esto incluye aspectos que van desde la gestión de fallos, la planificación, la optimización, así como la implementación de pilotos de nuevos estándares.

- **Objetivo 4: Evaluar la experiencia del servicio desde el punto de vista del usuario cuando se producen aglomeraciones temporales debido a eventos sociales.**

  Las concentraciones de personas, al ser eventos sociales ajenos al funcionamiento de las redes celulares, provocan degradaciones experimentadas por los usuarios que hacen uso de los servicios soportados por estas redes.

  En este sentido, esta tesis aporta un novedoso estudio de campo realizado en un escenario real situado en un estadio de fútbol con un montaje que incluye sondas conectadas a varios operadores. Asimismo, se ponen en práctica los fundamentos del marco de trabajo propuesto en el Obj.3 y, mediante el despliegue de varias sondas virtualizadas, se ha llevado a cabo una extensa campaña de medidas de la calidad percibida por los usuarios en las fechas en las que tuvo lugar un evento.

  Se ha comprobado el grado de afectación de múltiples servicios cuando se produce un evento, poniendo de manifiesto los factores que influyen en el mismo. También se ha verificado que existen diferencias sustanciales en los resultados obtenidos en cada servicio en función de la franja horaria, así como su correlación con los parámetros radioeléctricos.

- **Objetivo 5: Realizar la codificación y adaptación de la herramienta de simulador full-stack RAN para la evaluación realista de la calidad de experiencia de los servicios en bandas no licenciadas.**

  Una de las innovaciones más disruptivas introducidas por los estándares de la tecnología celular 3GPP ha sido la introducción de la operación en bandas de espectro sin licencia. Esto implica una serie de mecanismos que, a diferencia de los tradicionalmente implementados por los sistemas celulares planificados propietarios, requieren la capacidad de gestionar el acceso aleatorio al medio. Al no ser todavía una tecnología probada, son pocos los fabricantes que implementan este tipo de estándares, por lo que en el momento de abordar esta investigación no había posibilidad de conocer el funcionamiento real más allá de simulaciones simplificadas.

Basado en el módulo LENA del simulador full stack ns3, se proporciona la creación de un escenario de coexistencia ultradensa en interiores de la tecnología LAA con WiFi con la posibilidad de transmitir FTP y vídeo.

Esta adaptación permite la evaluación, incluyendo efectos de capa cruzada y de canal, de la calidad percibida por los usuarios. Las mediciones se complementan con diversas métricas a nivel de IP como la pérdida de paquetes, el retardo de extremo a extremo o el rendimiento.

- **Objetivo 6: Evaluar el rendimiento del servicio en escenarios de coexistencia utilizando bandas no licenciadas.**

  El carácter experimental de la operación celular en bandas no licenciadas, unido al previsible impacto de los estándares asociados hacía que no existieran estudios que evalúen la percepción de la calidad del servicio desde el punto de vista del usuario en el momento en el que se llevó a cabo este trabajo.

  A partir del desarrollo simulado, se proporciona la elaboración de un conjunto de datos de rendimiento de servicios de streaming de vídeo y FTP a partir de un entorno denso de coexistencia con usuarios WiFi. Se demuestra que existen problemas de equidad y grados de rendimiento en función de las condiciones de carga en un entorno interior.

- **Objetivo 7: Proporcionar un mecanismo de señalización optimizado para mejorar el rendimiento del servicio al usuario en bandas no licenciadas.**

  Como contribución final se proporciona un estudio exhaustivo de la señalización DRS en banda necesaria para operar en bandas sin licencia. En este estudio se comprueba el impacto de las configuraciones de señalización en el rendimiento y la latencia percibidos por el usuario a diferentes niveles de carga.

  Los resultados muestran que es posible optimizar dicha configuración DRS para que tenga un menor impacto en el rendimiento del servicio del usuario, y que puede ser modulada dinámicamente.

B.4 Resultados

El trabajo llevado a cabo durante esta tesis ha dado lugar a diversas contribuciones que se sintetizan en las siguientes subsecciones.

B.4.1 Publicaciones en revistas

Publicaciones derivadas de esta tesis

El trabajo realizado en esta tesis ha dado lugar a cuatro artículos publicados en revistas de alto impacto más uno en proceso de revisión, que se enumeran en la Tabla B.1.

Table B.1: Publicaciones en revistas.

	Publicación	FI	Ranking revista
I	J. Villegas, E. Baena, S. Fortes and R. Barco, "Social-Aware Forecasting for Cellular Networks Metrics" *IEEE Communications Letters* vol. 25, no. 6, pp. 1931-1934, 2021	3.553	Q2 (39/94) Telecommunications
II	Baena, E.; Fortes, S.; Muro, F.; Baena, C; and R. Barco, "A novel synthetic image-based approach for location-aware management of cellular networks," *IEEE Network*, Under review 2022	10.294	Q1 (5/94) Telecommunications
III	E.Baena, S.Fortes, O.Alay, M.Xie, H.Lønsethagen, R.Barco, "Cellular Network Radio Monitoring and Management through Virtual UE Probes: A Study Case Based on Crowded Events." *Sensors*, vol. 21.10,3404 , 2021	3.847	Q2 (95/276) Engineering, electrical & electronic
IV	E.Baena, S.Fortes and R.Barco, "KQI Performance Evaluation of 3GPP LBT Priorities for Indoor Unlicensed Coexistence Scenarios" *Electronics*, vol. 9, 1701, 2021	2.69	Q3 (139/276) Engineering, electrical & electronic
V	E.Baena, S.Fortes and R.Barco, "Assessing the impact of DRS signaling in unlicensed indoor coexistence scenarios" *EURASIP Journal on Wireless Communications and Networking*, 2020	2.455	Q3 (141/273) Engineering, electrical & electronic

Publicaciones en revistas relacionadas con esta tesis

Paralelamente, el autor ha colaborado en proyectos de investigación a los que ha contribuido y que han dado lugar a varias publicaciones en revistas indexadas.

Table B.2: Publicaciones en revistas relacionadas con esta tesis

	Publicación	FI	Ranking revista
VI	S. Fortes, J. Santoyo-Ramón, D. Palacios, E. Baena et al., "The Campus as a Smart City: University of Málaga Environmental, Learning, and Research Approaches" *Sensors, 19 (6), 1349, 2019*	3.275	Q2 (36/91) Engineering, Electrical & Electronic
VII	A. Herrera-Garcia, S. Fortes, E. Baena, J. Mendoza, C. Baena and R. Barco, "Modeling of Key Quality Indicators for End-to-End Network Management: Preparing for 5G" *IEEE Vehicular Technology Magazine*, 14 (4), 76-84, 2019	7.921	Q1 (7/90) Telecommunications
VIII	C. Baena, S. Fortes, E. Baena and R. Barco, "Estimation of Video Streaming KQIs for Radio Access Negotiation in Network Slicing Scenarios" *IEEE Communications Letters*, vol. 24 (6), pp. 1304-1307, 2020	3.436	Q2 (14/82) Telecommunications
IX	Peñaherrera-Pulla, O.S.; Baena, C.; Fortes, S.; Baena, E.; Barco,R "Measuring Key Quality Indicators in Cloud Gaming: Framework and Assessment Over Wireless Networks" *Sensors*, vol. 21, 1387, 2020	3.576	Q2 (77/266) Engineering, Electrical& Electronic
X	Fortes, S.; Baena, C.; Villegas, J; Baena, E.; Zeeshan, A.M; Barco, R "Location-Awareness for Failure Management in Cellular Networks: An Integrated Approach" *Sensors*, vol. 21, 1501, 2021	3.576	Q2 (77/266) Engineering, Electrical & Electronic
XI	Aguayo, L.; Fortes, S.; Baena, C.; Baena, E.; Barco.R, "A Multivariate Time-Series Based Approach for Quality Modeling in Wireless Networks" *Sensors*, vol. 21, 2017 , 2021	3.576	Q2 (77/266) Engineering, Electrical & Electronic
XII	R. Torres, S. Fortes, E. Baena and R. Barco, "Social-Aware Load Balancing System for Crowds in Cellular Networks" *IEEE Access*, vol. 9, pp. 107812-107823, 2021	3.367	Q2 (36/91) Telecommunications
XIII	Peñaherrera-Pulla, O.S.; Baena, C.; Fortes, S.; Baena, E.; Barco, R, "KQI assessment of VR services: A case study on 360-Video over 4G and 5G" *IEEE Transactions on Network and Service Management*, In press 2022	4.195	Q2 (47/161) Computer Science, Information Systems
XIV	F.Muro, E.Baena, S.Fortes, C.Baena and R.Barco, "Noisy Neighbour impact assessment and prevention in virtualized mobile networks " *IEEE Transactions on Network and Service Management*, In press 2022	4.195	Q2 (47/161) Computer Science, Information Systems

B.4.2 Conferencias y workshops

Conferencias

También se han presentado varios trabajos en congresos nacionales e internacionales, como se muestra a continuación.

Table B.3: Conferencias derivadas de esta tesis

XV	E.Baena, S. Fortes, R. Barco, “Evaluación del protocolo Listen Before Talk en el estándar 3GPP Licensed Assisted”, *XXXIII SImposium nacional de la Unión Científica Internacional de Radio, Granada*, 2018
XVI	E.Baena, S. Fortes, C.Baena, R. Barco, “Optimización de señalización en el canal común descendente para el estándar LTE-LAA”, *XXXIV SImposium nacional de la Unión Científica Internacional de Radio, Sevilla*, 2019
XVII	E.Baena, S. Fortes, R. Barco, “Impact of Unlicensed-band Listen Before Talk Priority Classes in Ultra-dense Scenarios” *COST IRACON 11th MC meeting and 11th technical meeting*, Gdansk, Poland, 2019
XVIII	E.Baena, S. Fortes, R. Barco, “DRS signaling optimization in unlicensed dense coexistence scenarios” *3rd POST IRACON Meeting*, Online, 2021

Otras conferencias

Table B.4: Conferencias relacionadas

	Conferencias relacionadas
XIX	S. Fortes,E.Baena, R. Barco, “Might 5G Technologies Increase or Reduce the Digital Divide?” *IEEE Global Communications Conference (IEEE GLOBECOM)*, Abu Dhabi, UAE, 2018
XX	A. Herrera-García, S. Fortes, E. Baena, J. Mendoza, C. Baena, R. Barco, “Estimation of Service Quality Indicators in Cellular Networks’ *COST IRACON 11th MC meeting and 11th technical meeting*, Gdansk, Poland, 2019
XXI	A.Moreno-Sancho, E.Baena, S. Fortes, R. Barco, “Sonda experimental de monitorización de redes móviles para eventos”, *XXXV Simposium Nacional de la Unión Científica Internacional de Radio, Malaga*, 2020
XXII	F.Muro; E.Baena, S. Fortes, L.Mikkelsen, M.Dieudonne,J.Torrecilla, A.Sethu, R.Barco, “Evaluación del impacto del Noisy Neighbour en redes móviles virtualizadas”, *XXXVI Simposium Nacional de la Unión Científica Internacional de Radio, Vigo*, 2021

B.4.3 Proyectos relacionados

Esta tesis ha sido parcialmente financiada por los siguientes proyectos:

- Optimi-Ericsson, ref.59288, Junta de Andalucía (Agencia IDEA, Consejería de Ciencia, Innovacion y Empresa) y ERFD.
- Proyecto de Investigación de Excelencia P12-TIC-2905, Junta de Andalucía.

Además, el autor ha participado en los siguientes proyectos:

- Inteligencia Artificial para el Análisis y Monitorización de Redes de Comunicación 5G (IA2MON-5G)
- MUSE - Massive USer Experience Assessment and Prediction for Mobile Networks
- Ministry of Economy and Competitiveness TEC2015-69982-R

- Gestión integral avanzada de funciones SON (Self-Organizing Networks) para redes móviles futuras, P12-TIC-2905, Proyectos de Excelencia, Junta de Andalucía.
- IDADE-5G UMA18-FEDERJA-201 Programa Operativo FEDER Andalucia 2014-2020
- PENTA P18-FR-4647 Proyectos de investigación en colaboración con el tejido productivo
- SMART Incentivos a los agentes públicos del Sistema Andaluz del Conocimiento, para la realización de proyectos de I+D+i., en el ámbito del Plan Andaluz de Investigación, Desarrollo e Innovación PAIDI 2020

B.4.4 Estancias de investigación

Esta tesis permitió realizar una estancia de tres meses en el departamento Mobile Systems and Analytics (MOSAIC) en Simula Metropolitan Center for Digital Engineering (Oslo, Noruega). Durante la misma el trabajo fue supervisado por la Dra. Özgü Alay colaborando con el operador de red celular Telenor. El trabajo de la sección 5.1 recoge principalmente los resultados de esta estancia.

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