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TESIS DOCTORAL

5G NETWORKS AUTOMATIC PERFORMANCE IMPROVEMENT

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Por la presente, la **Dra. Dª. Raquel Barco Moreno** y la **Dra. Dª. Isabel de la Bandera Cascales**, profesoras del Departamento de Ingeniería de Comunicaciones de la Universidad de Málaga, **CERTIFICAN:**

Que **Dª. Jessica Mendoza Ruiz** 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:

"5G networks automatic performance improvement"

En dicho trabajo se han propuesto aportaciones originales para el desarrollo de técnicas de auto-optimización que permiten mejorar la eficiencia y el funcionamiento de redes móviles. Los resultados expuestos han dado lugar a las siguientes publicaciones en revistas y aportaciones a congresos, considerándose la tesis como idónea para presentarla en la modalidad de "Tesis por compendio de publicaciones".

1. J. Mendoza, I. de-la-Bandera, C.S. Álvarez-Merino, E.J. Khatib, J. Alonso, S. Casalderrey-Díaz, and R. Barco, "5G for Construction: Use Cases and Solutions," Electronics, vol. 10, no. 14, p. 1713, Jul. 2021.
2. J. Mendoza, I. de-la-Bandera, D. Palacios, and R. Barco, "Forecasting Framework for Mobile Networks based on Automatic Feature Selection," IEEE Transactions on Network and Service Management, Under review, 2022.
3. J. Mendoza, D. Palacios, I. de-la-Bandera, E. Baena, E.J. Khatib, and R. Barco, "Modeling the UE-perceived Cellular Network Performance following a Controller-based Approach," EURASIP Journal on Wireless Communications and Networking, vol. 2019, no. 1, pp. 1-12, Dec. 2019.
4. J. Mendoza, I. de-la-Bandera, D. Palacios, A. Herrera-García, and R. Barco, "On the Capability of QoE Improvement based on the Adjustment of RLC Parameters," Sensors, vol. 20, no. 9, p. 2474, Apr. 2020.
5. J. Mendoza, I. de-la-Bandera, D. Palacios, and R. Barco, "QoE Optimization in a Live Cellular Network through RLC Parameter Tuning," Sensors, vol. 21, no. 16, p. 5619, Aug. 2021.
6. J. Mendoza, I.Z. Kovács, M. López, T.B. Sørensen, R.O. Adeogun, I. de-la-Bandera, and R. Barco, "Proactive Dual Connectivity for Automated Guided Vehicles in Outdoor Industrial Environment," IEEE Access, vol. 10, pp. 54149-54163, May 2022.
7. J. Mendoza, I. de-la-Bandera, J. Burgueño, C. Morillas, D. Palacios, and R. Barco, "Anomaly Detection and Analysis Framework for Mobile Networks," in 2021 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit), Porto (Portugal), Jun. 2021.
8. J. Mendoza, D. Palacios, I. de-la-Bandera, and R. Barco, "Selección Automática de Características para una Gestión Proactiva Eficiente de Redes 5G," in XXXIV Simposium Nacional de la Unión Científica Internacional de Radio (URSI 2019), Sevilla (Spain), Sep. 2019.

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

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Realizada bajo la tutorización de RAQUEL BARCO MORENO y dirección de RAQUEL BARCO MORENO E ISABEL DE LA BANDERA CASCALES (si tuviera varios directores deberá hacer constar el nombre de todos)

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para juzgar la Tesis Doctoral titulada *"5G networks automatic performance improvement"* realizada por Dña. Jessica Mendoza Ruiz, y dirigida por las doctoras Dña. Raquel Barco Moreno y Dña. Isabel de la Bandera Cascales, acordó por

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A mi familia.

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Contents

Abstract

The world is currently in a process of digital transformation of various socio-economic sectors. In this context, the Fifth Generation (5G) of mobile networks is emerging as an enabling technology for this transformation, covering a wide variety of services and use cases related to different sectors of the economy (e.g., industry, agriculture or automotive). The exponential growth of networks makes their management tasks increasingly complex. To minimize capital expenditures (CAPEX) and operational expenditures (OPEX) while providing quality services to users, mobile network operators (MNOs) focus on the use of the so-called self-organizing networks (SON).

The SON concept refers to the automation of network management tasks, which are classified into three categories: self-configuration, self-healing, and self-optimization. Self-configuration is in charge of automating the deployment of new network elements and the configuration of their parameters. Self-healing automates the management of potential network failures, performing detection, diagnosis, compensation, and recovery tasks. Finally, self-optimization aims to maximize network performance. Thus, self-optimization is responsible for dynamically adapting the network to environmental variations. To this end, it automatically modifies the network configuration parameters.

To adapt to the challenges launched by the new services and use cases contemplated in 5G, a modernization of the traditional SON algorithms is needed. This thesis addresses the adaptation of SON to the new needs of 5G. Specifically, this thesis focuses on the development of automatic control techniques to improve network performance. To this end, this thesis considers different lines of research. On the one hand, one of the main current trends in the development of SON algorithms is the use of user-centric approaches, which focus on the optimization of metrics such as quality of experience (QoE) that provide a vision of the level of user satisfaction. On the other hand, as networks grow, so do the number of information sources

and data collected by them. The use of non-relevant information in the development of SON algorithms can lead to an increase in the complexity of the algorithms, as well as a loss in the efficiency of these algorithms. Therefore, the use of dimensionality reduction techniques is considered as a key factor for the development of accurate SON algorithms. Finally, meeting the very low latency and high data rate requirements of some of the new 5G use cases, make necessary a change of approach in the development of SON algorithms, moving from a reactive to a proactive approach to anticipate possible failures or degradations of the network performance.

To meet the main objective and provide answers to the previously stated lines of research, this thesis addresses different phases of the optimization process, being organized in three parts. The first part includes all the tasks related to network performance analysis. On the one hand, this thesis analyzes the challenges of 5G implementation in new scenarios. Specifically, the use of 5G to drive the digital transformation of the construction sector is proposed. On the other hand, an analysis of the anomalies detected in the networks has been carried out, proposing a framework capable of detecting anomalies of various types in a wide variety of key performance indicators (KPIs). The second part focuses on the development of frameworks to improve the performance and the evaluation of optimization algorithms. In this regard, first, this thesis proposes the use of dimensionality reduction techniques to improve the accuracy of the prediction algorithms used in proactive management methods. Next, a mechanism for the establishment of a test environment to verify the performance of the SON algorithms before their implementation in real networks is presented. The third part of this thesis focuses on the development of optimization algorithms. First, a QoE optimization algorithm is presented. This algorithm is centered on the adjustment of the radio link control (RLC) configuration parameters. Secondly, a proactive algorithm for automatically activate multi connectivity (MC) in an industrial environment is proposed.

Resumen

El mundo se encuentra actualmente en un proceso de transformación digital de diversos sectores socioeconómicos. En este contexto, la quinta generación (*Fifth Generation*, 5G) de redes móviles se presenta como una tecnología habilitadora de esta transformación, abarcando una gran variedad de servicios y casos de uso relacionados con diferentes sectores de la economía (como por ejemplo, la industria, la agricultura o la automoción). El crecimiento exponencial de las redes hace que sus tareas de gestión sean cada vez más complejas. Para minimizar los gastos de capital (*capital expenditures*, CAPEX) y los gastos de operación (*operational expenditures*, OPEX) al tiempo que se prestan servicios de calidad a los usuarios, los operadores de redes móviles (*mobile network operators*, MNO) se centran en el uso de las llamadas redes autoorganizadas (*self-organizing networks*, SON).

El concepto de SON se refiere a la automatización de las tareas de gestión de la red, que se clasifican en tres categorías: autoconfiguración, autocuración y autooptimización. La autoconfiguración se encarga de automatizar el despliegue de nuevos elementos de la red y de la configuración de sus parámetros. La autocuración automatiza la gestión de los posibles fallos de la red, realizando tareas de detección, diagnóstico, compensación y recuperación. Por último, la autooptimización tiene como objetivo maximizar el rendimiento de la red. Así, la autooptimización se encarga de adaptar dinámicamente la red a las variaciones del entorno. Para ello, modifica automáticamente los parámetros de configuración de la red.

Para abordar los restos lanzados por los nuevos servicios y casos de uso contemplados en las redes 5G, es necesario llevar a cabo una modernización de los algoritmos tradicionales de las SON. Esta tesis aborda la adaptación de las SON a las nuevas necesidades del 5G. En concreto, esta tesis se centra en el desarrollo de técnicas de control automático para mejorar el rendimiento de la red. Para ello, se contemplan diferentes líneas de investigación. Por un lado, una de las principales tendencias actuales en el desarrollo de algoritmos de SON es el uso de enfoques centrados en el usuario, que se centran

en la optimización de métricas como la calidad de experiencia (*quality of experience*, QoE) que proporcionan una visión del nivel de satisfacción del usuario. Por otro lado, a medida que las redes crecen, también lo hace el número de fuentes de información y de datos recogidos por ellas. El uso de información no relevante en el desarrollo de algoritmos de SON puede conducir a un aumento de la complejidad de los algoritmos, así como a una pérdida de eficiencia de los mismos. De este modo, el uso de técnicas de reducción de la dimensionalidad se considera un factor clave para el desarrollo de algoritmos de SON precisos. Por último, el cumplimiento de los requisitos de muy baja latencia y alta velocidad de datos de algunos de los nuevos casos de uso de las redes 5G, hacen necesario un cambio de enfoque en el desarrollo de algoritmos de las SON, pasando de un enfoque reactivo a uno proactivo para anticiparse a posibles fallos o degradaciones del rendimiento de la red.

Para cumplir con el objetivo principal y dar respuesta a las líneas de investigación planteadas anteriormente, esta tesis aborda diferentes fases del proceso de optimización. Para ello, esta tesis está organizada en tres partes. La primera parte incluye todas las tareas relacionadas con el análisis del rendimiento de la red. Así, por un lado, esta tesis analiza los retos de la implementación del 5G en nuevos escenarios. En concreto, se propone el uso del 5G para impulsar la transformación digital del sector de la construcción. Por otro lado, se ha realizado un análisis de las anomalías detectadas en las redes, proponiendo un sistema capaz de detectar anomalías de diversa índole en una amplia variedad de indicadores clave del rendimiento (*key performance indicators*, KPI). La segunda parte se centra en el desarrollo de mecanismos para mejorar el rendimiento y la evaluación de los algoritmos de optimización. En este sentido, en primer lugar, esta tesis propone el uso de técnicas de reducción de la dimensionalidad para mejorar la precisión de los algoritmos de predicción utilizados en los métodos de gestión proactiva. A continuación, se presenta un mecanismo para el establecimiento de un entorno de pruebas para verificar el rendimiento de los algoritmos de SON antes de su implementación en redes reales. La tercera parte de esta tesis se centra en el desarrollo de algoritmos de optimización. En primer lugar, se presenta un algoritmo de optimización de la QoE. Este algoritmo se centra en el ajuste de los parámetros de configuración de la capa de control del radioenlace (*radio link control*, RLC). En segundo lugar, se propone un algoritmo proactivo para activar automáticamente la multiconectividad (*multi connectivity*, MC) en un entorno industrial.

Acronyms

3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
5G NSA	5G non-standalone
5G SA	5G standalone
5GC	5G core network
5GS	5G system
AF	Application function
AGV	Automated guided vehicle
AM	Acknowledged mode
AMF	Access and mobility management fuction
ANN	Artificial neural networks
AS	Access stratum
AUSF	Authentication server function
BPSK	$\pi/2$-binary phase-shift keying
CA	Carrier aggregation
CAPEX	Capital expenditures
CM	Configuration management parameter
CMC	Connection mobility control
CN	Core network
DC	Dual connectivity
DL	Deep learning
DRB	Data radio bearer
E2E	End-to-end
E-UTRAN	Evolved universal terrestrial radio access network
eMBB	Enhanced mobile broadband
EN-DC	E-UTRAN-NR DC
eNB	Evolved node B

EPC	Evolved packet core
EPS	Evolved packet system
gNB	Next generation node B
HARQ	Hybrid automatic repeat request
HO	Handover
HSS	Home subscriber server
GRU	Gated recurrent unit
ICT	Information and communication technology
IP	Internet protocol
IoT	Internet of Things
KPI	Key performance indicator
KQI	Key quality indicator
LTE	Long-Term Evolution
LTE-A	Long-Term Evolution Advanced
LR	Linear regression
MAC	Medium access control
MC	Multi connectivity
MCG	Master cell group
MeNB	Master eNB
MIMO	Multiple-input multiple-output
ML	Machine learning
MME	Mobility management entity
mMTC	Massive machine-type communication
MN	Master node
MNO	Mobile network operator
MR-DC	Multi-radio DC
NAS	Non-access stratum
ng-eNB	Next-generation eNB
NG-RAN	Next-generation radio access network
NGMN	Next-Generation Mobile Network
NSSAAF	Network slice specific authentication and authorization function
NSSF	Network slice selection function
NR	New radio
NR-DC	NR-NR DC
OFDM	Orthogonal frequency-division multiplexing
OFDMA	Orthogonal frequency-division multiple access

OPEX	Operational expenditures
P-GW	Packet data network gateway
PAPR	Peak-to-average power ratio
PCell	Primary cell
PCF	Policy Control function
PDCP	Packet data coverage protocol
PDN	Packet data network
PHY	Physical
PM	Performance management parameter
PRB	Physical resource block
QAM	Quadrature amplitude modulation
QPSK	Quadrature phase-shift keying
QoE	Quality of experience
QoS	Quality of service
RAC	Radio admission control
RAN	Radio access network
RAT	Radio access technology
RBC	Radio bearer control
RE	Resource element
RL	Reinforcement learning
RLC	Radio link control
RRH	Remote radio head
RRC	Radio resource control
RRM	Radio resource management
RSRP	Reference signal received power
S-GW	Serving gateway
SC-FDMA	Single carrier frequency division multiple access
SCell	Secondary cell
SCG	Secondary cell gruop
SeNB	Secondary eNB
SMF	Session management function
SN	Secondary node
SON	Self-organizing networks
SRB	Signaling radio bearer
SVR	Support vector regression
TB	Transport block

TTI	Transmission time interval
UE	User equipment
UM	Unacknowledged mode
UMAHetNet	University of Malaga heterogeneous network
UPF	User plane function
URLLC	Ultra-reliable low-latency communications
VoIP	Voice over IP

Chapter 1

Introduction

This chapter provides an introduction to the work carried out during this thesis. First, in Section 1.1 the motivation is presented, indicating how mobile networks optimization techniques have evolved over time. Next, the objectives pursued in this thesis are outlined in Section 1.2. Finally, the structure of the document is described in Section 1.3.

1.1 Motivation

Since its inception, mobile communications have been constantly evolving, providing more and better quality services to its users. The times have long gone when mobile communications were only for making phone calls and sending text messages. Today, cell phones are part of our daily lives, providing us access to the Internet and to thousands of applications such as instant messaging, social networks, banking or shopping. The expansion of mobile communications services has spread beyond communications between people to include communications between people and machines such as remote control applications, or between machines such as vehicular communications. Thus, mobile communications has become a key element in driving the digital transformation of society and economy.

In this context, the Fifth Generation (5G) technologies arise with the aim of not only providing enhanced mobile broadband (eMBB) services compared to previous generations, but also to cover new use cases related to critical communications, that are known as ultra-reliable low-latency communications (URLLC), and the massive use of machine-type devices as is the case of the Internet of Things (IoT), these services are known as massive machine-type communications (mMTC) [1,2]. In this way, 5G is intended to cover a wide variety of services, becoming an enabling technology to carry out the digitalization and automation of different industry sectors, such as agriculture, energy, manufacturing, healthcare or the automotive [3].

The unstoppable evolution of mobile communications makes their management and operation tasks increasingly complex. To ensure minimal capital expenditures (CAPEX) and minimal operational expenditures (OPEX) while meeting consumers demand and providing high quality services, mobile network operators (MNOs) focus their efforts on tasks automation, which leads to what is known as self-organizing networks (SON) [4].

The principles of SON were first established by the Next-Generation Mobile Network (NGMN) Alliance in 2008 [5,6]. Later, the Third Generation Partnership Project (3GPP) included the requirements of SON in its standards [7], grouping the SON functionalities into three categories: self-configuration [8], self-optimization [8] and self-healing [9]. On the one hand, self-configuration covers all those tasks related to the automatic configuration of newly deployed network elements. On the other hand, self-optimization includes those functions related to the readjustment of network configuration parameters, thus making the network capable of adapting dynamically to changes in the environment (e.g., weather, traffic patterns or interference) and providing quality services at any time. Finally self-healing encompasses those tasks aimed at detecting possible failures in the network, diagnosing the root cause of these failures and determining compensation and recovery actions. This thesis is centered in self-optimization tasks.

Given the importance of SON techniques, over the last few years, multiple high-impact international projects have focused on the research and development of these techniques in Long-Term Evolution (LTE) and 5G networks. Among these projects are the following: SEMAFOUR [10], SELFNET [11], ONE5G [12], SONNET [13], IMMINENCE [14], and LOCUS [15]. Despite the great advances of these projects, the fact that mobile communications networks are constantly evolving, means that SON algorithms also need to evolve in order to adapt to the new services, use cases and requirements of the networks.

Traditionally, mobile network optimization has focused on the analysis and improvement of radio access network (RAN) key performance indicators (KPIs), such as blocking rate or call drop rate [16]. However, in recent years, due to the expansion of mobile communications and the increasingly stringent demands from mobile users, the focus in terms of network optimization has been moving gradually closer to the user. Thus, works such as [17] focus on the optimization of key quality indicators (KQI) that provide application-level information about the quality of services offered to users. Currently, network management experts focus their attention on optimizing quality of experience (QoE) [18, 19]. This metrics allow to perform a user-centric management with an end-to-end (E2E) global view.

As networks grow, so do the number of sources of information and data collected by them. All this information is useful for the development of SON algorithms that control different aspects of the network. However, when designing a specific algorithm, the correct selection of the information to be used is of vital importance. The use of non-relevant information leads not only to the development of more complex algorithms and models, since they have a greater number of input parameters, but also to a loss of efficiency and effectiveness of these algorithms, which will be less precise and/or accurate in their results. Traditionally, the selection of this information has been done manually, as in [20–24]. These manual techniques are very time-consuming tasks. For this reason, network management experts usually use the same KPIs as inputs to the algorithms, which might not always give the best results. To solve this problem, the use of dimensionality reduction techniques is needed. These techniques aims at selecting or extracting the most relevant characteristics to solve a given problem.

The emergence of new services in 5G with increasingly stringent requirements for low latency and high data rates means that traditional SON algorithms based on reactive methods that execute an action when a fault or performance degradation is detected in the network, are not sufficient [25–27]. Thus, recent works focus on proactive network management methods, capable of anticipating possible network events. In this context, multiple authors have centered their attention in implementing forecasting frameworks to predict different aspect of the network such as cell load [28], radio channel quality [29], users location [30], network traffic [31–37], QoE [38, 39], services demand [40], or RAN metrics [41]. In addition to these forecasting frameworks, in the literature there are also works proposing proactive methods to perform self-optimization tasks, such as dynamic antennas [42] and beam [43] management, load balancing [44], energy saving [45], cloud-RAN configuration [46, 47], resources allocation [48, 49], or handover (HO) management [50, 51]; and self-healing, such as network fault detection [52, 53]. Despite the extensive literature associated with this topic, proactive network management is still considered a hot topic today, where the aim is to achieve more accurate prediction algorithms so that their results can be more reliable for decision making. In addition, the development of proactive algorithms for the management of new 5G functionalities, such as multi connectivity (MC) or network slicing, is considered necessary.

1.2 Challenges and objectives

The main objective of this thesis is to improve network performance by using automatic control techniques. For this purpose, different steps of the optimization process are addressed in this thesis. First, tasks related to the study of the characteristics and requirements of the networks and their environment are carried out. Secondly, frameworks are developed to improve the performance and the evaluation of the optimization algorithms. Finally, self-optimization algorithms are developed with the following purposes: improvement of user QoE and improvement of the service offered in new 5G scenarios through the use of MC.

5G aims to cover a wide variety of services and use cases. The characteristics and requirements of these new 5G scenarios vary depending on the environment and the services provided to users. Thus, the analysis of the new 5G scenarios prior to the development of optimization algorithms to obtain a deep understanding of the operation of the networks, as well as their main characteristics and requirements to be satisfied becomes an essential task. One of the main use cases that 5G technology is intended to serve is the digital transformation of industry, giving rise to what is known as the fourth industrial revolution or Industry 4.0 [54, 55]. The implementation of 5G technology in different industry sectors has been addressed by a multitude of works in the literature [56–61]. However, most of these works focus on sectors such as logistics or manufacturing, forgetting other sectors that today still have a low level of automation and digitization. This is the case of the construction sector. This sector, despite being one of the largest in the industry, is one of the least affected by the new industrial revolution [62,63]. This is due to the particularities of this sector, where most of the work is carried out on construction sites, that are changing and non-permanent environments. Thus, the first objective of this thesis (Obj. 1) is to perform an analysis of the needs and limitations of the construction sector to carry out the implementation of 5G.

The growth of mobile networks and their expansion into new scenarios are making networks increasingly complex. This leads to the emergence of new network failures. The analysis of anomalies helps to gain more knowledge in networks behavior, helping to understand how the readjustment of certain aspects of the network could lead to errors or performance degradation. The first step in network anomaly analysis is anomaly detection. Anomaly detection is based on the analysis of the behavior of certain KPIs. Although anomlay detection has been a topic covered extensively in the literature by multiple authors, most of these works focus on detecting certain types of anomalies, such as isolated anomalies [64,65] or long-lasting anomalies [66,67], and also on certain types of KPIs, the most studied being KPIs that exhibit periodic behavior over time [66–70]. Following with this line, the second objective (Obj. 2) of this thesis is to develop a system that allows the joint detection of different types of anomlaies in KPIs with different nature. From the results of this system it will be possible to perform an in-depth analysis of the detected failures.

As mentioned above, in order to meet the high data rate and very low latency requirements of some of the new 5G services, the evolution towards proactive optimization algorithms is indispensable. These algorithms are based on the use of time series prediction techniques capable of predicting future events through the analysis of the current and past state of the network [71]. For the proactive optimization of networks to be feasible, the prediction made must be reliable and have a high degree of accuracy. In order to achieve the most accurate predictions possible, the use of many time series prediction techniques have been proposed in the literature. These range from simple methods based on linear models such as ARIMA [72, 73] or the Holt-Winters algorithm [49,74] to more complex methods based on machine learning (ML) and deep-learning (DL) algorithms such as support vector regression (SVR) [75, 76], or artificial neural networks (ANN) [48, 77]. 5G networks are expected to increase the number of sources of information, and therefore the amount of data available to perform network management tasks [78]. This high number of information sources will allow better control of the network and its environment. However, this also complicates the task of selecting the relevant information for a given function. The use of non-relevant information as input to a prediction algorithm brings with it two main problems [79]: the increase in complexity of the generated models and the loss of accuracy due to the noise that this non-relevant information introduces into the models. To perform the input parameter selection, the use of dimensionality reduction techniques such as feature selection [80–82] and feature extraction [83] are proposed in the literature. To this end, authors typically rely on the use of metrics that measure the average value of the different features, obviating the temporal dimension of the parameters. Thus, the third objective (Obj. 3) of this thesis is to improve prediction accuracy by using dimensionality reduction schemes capable of considering not only the different indicators, but also their temporal dimension. In this way, a better feature selection may be obtained which may contribute to increase the prediction reliability.

The complexity of 5G network management tasks highlights the need for automatic management algorithms. Before putting these algorithms into production across the entire network, testing is necessary to evaluate their performance. However, many MNOs are reluctant to evaluate these algorithms in their networks, as they could cause performance degradations due to network misconfiguration performed automatically by the algorithm. Thus, many algorithms developed by researchers and evaluated in simulated environments are never implemented in real networks. In cases where MNOs decide to evaluate algorithms on their networks, the tests are performed on specific areas of the network. This way of evaluating algorithms presents some limitations, since different areas of the networks may present very different behaviors, so that the conclusions obtained for one area may not be extrapolated to another. To solve this problem, the fourth objective (Obj. 4) of this thesis is to develop a framework for modeling test environments or testbeds, so that it is possible to replicate the behavior of a real network or an area of it from the user equipment (UE) point of view in the testbed, thus, obtaining an E2E view of the network behavior.

Self-optimization is a process by which different network configuration parameters are automatically readjusted to dynamically adapt the network to the environment, ensuring maximum network efficiency. During the last few years, one of the main trends in the design of SON algorithms is the use of user-centric approaches [84], which rely on user metrics such as the QoE to manage the network. Intrinsic phenomena of wireless communications such as interference, noise or fading have a direct impact on signal quality, which could result in QoE degradations. In mobile networks, the radio link control (RLC) layer is responsible for providing a reliable link between the transmitter and receiver, mitigating the impact of these phenomena. To this end, the RLC layer performs error detection and, in some cases, error correction tasks, depending on the requirements of the services. Despite the possible impact of RLC layer tuning on user QoE, this has not been studied in the state of the art, where most work focuses on functions related to other layers of the mobile technologies protocol stack such as application layer [85–89], medium access control (MAC) layer [90–92], or physical layer [93]. In this way, the fifth objective (Obj. 5) of this thesis is to conduct a study on the impact of adjusting the configuration parameters of the RLC layer on the QoE of users of different services in a mobile network. Following this line, the sixth objective (Obj. 6), consists in the development of an optimization algorithm that allows the automatic adjustment of the configuration parameters of the RLC layer in order to maximize the QoE perceived by the users of different types of services.

Another open issue in mobile network optimization is the adaptation of networks for new 5G use cases. Specifically, this thesis focuses on the use case of automated guided vehicles (AGVs) in industrial environments. These vehicles, are responsible for transporting materials and goods within factory facilities [94]. The AGVs communicate with a central guidance control system, to which they transmit video images and from which they receive guidance commands [95]. Thus, for the correct operation of these robots, it is necessary that the communication with the central guidance control system takes place in real time, being necessary high data rates for the correct transmission of the video [96]. To meet these requirements, the use of MC is proposed. MC allows a UE to connect with more than one radio link to the network, improving communication aspects such as throughput, reliability and latency [97, 98]. However, an uncontrolled use of MC can lead to an inefficient use of network resources, which may result in a worsening of the overall network performance [99, 100]. Thus, the seventh objective (Obj. 7) of this thesis consists in the development of a MC management algorithm for the use case of AGVs in an industrial environment. On the other had, communications failures may cause AGVs' accidents. As a result, the communications between AGVs and their central guidance control system are considered as critical communications. In order to ensure proper communication at all times, proactive management is necessary to anticipate possible performance degradations or network failures. Therefore, the eighth objective (Obj. 8) of this thesis consists in proposing a proactive optimization algorithm that allows to guarantee the communications in the use case of AGVs in an industrial environment.

In summary, the objectives that address the previous challenges are the following (see Fig. 1.1):

Obj. 1: To study the feasibility of using 5G to conduct the digitization of the construction sector. This study should identify the main use cases related to the digitization of the construction sector. In addition, it should include the main 5G functionalities that will satisfy the needs of the sector. In this way, this study is intended to lay the groundwork for the digitization of the construction sector through the use of

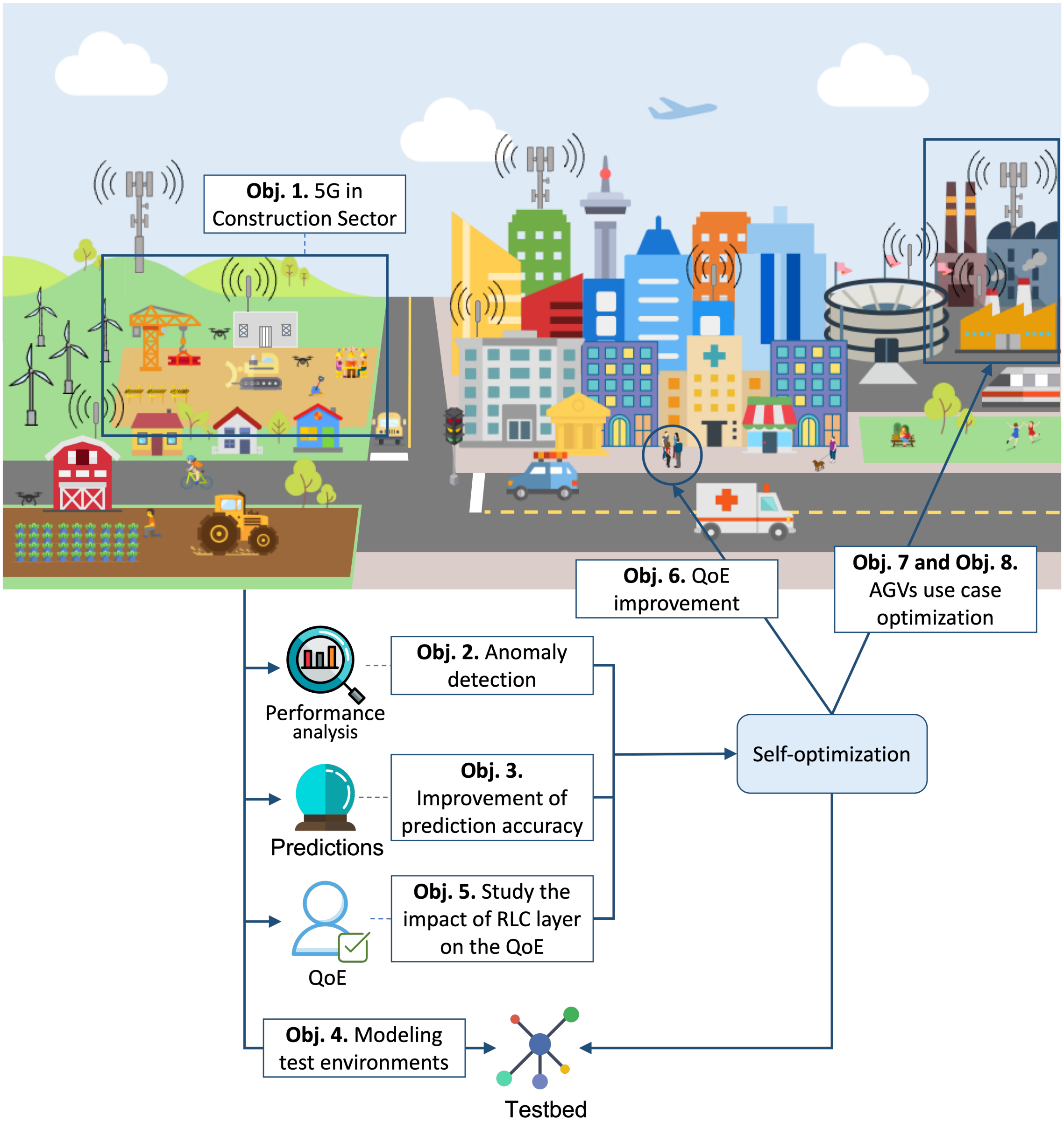


Figure 1.1: Objectives of this thesis.

5G technology.

Obj. 2: To propose a system for detecting different types of anomalies in KPIs of different nature. The system should be able to jointly detect the different types of anomalies occurring in a mobile network by analyzing the KPIs. As a result, valuable information will be obtained that will allow in-depth analysis of network performance, providing knowledge for the development of optimization algorithms.

Obj. 3: To propose a framework based on an efficient information processing to improve prediction accuracy. This framework will make use of dimensionality reduction techniques as a preliminary step to KPI prediction. Thus, the framework will simplify the prediction models and eliminate the noise introduced in them by the use of features not relevant to the prediction. As a result this framework will increase the accuracy of the predictive algorithms proposed in the state of the art.

Obj. 4: To propose a mechanism for modeling test environments. The mechanism will aim to ensure that the test network is perceived by the UE in the same way as a real network or an area of it. Thus, this algorithm will allow configuring a test environment in which the evaluation of different network management algorithms may be performed.

Obj. 5: To study the impact of RLC configuration parameters adjustment on the QoE. The objective of this study is to analyze the behavior of the RLC layer as well as the impact of readjusting its configuration parameters on the QoE perceived by users. In this way, this study aims to lay the foundations for the development of future optimization algorithms based on the adjustment of the RLC layer.

Obj. 6: To propose an algorithm for QoE improvement based on the adjustment of RLC configuration parameters. This objective is related to the Obj. 5. The idea is to design and develop an algorithm that automatically makes adjustments to the configuration parameters of the RLC layer in order to maximize the QoE perceived by the users. This algorithm will be developed based on the knowledge acquired in the study previously carried out in Obj. 5.

Obj. 7: To propose a MC activation algorithm for the AGVs use case in an industrial environment. This objective refers to the design and development of an algorithm to guarantee the fulfillment of the communication needs of AGVs deployed in an industrial 4.0 environment. Thus, the proposed algorithm should be able to dynamically and automatically control the activation of MC for those AGVs that require it.

Obj. 8: To propose a proactive optimization algorithm to avoid performance degradations in the AGVs use case in an industrial environment. This algorithm must be able to foresee future degradations in network performance and anticipate actions to prevent these degradations from occurring.

1.3 Document structure

This document has been organized in seven chapters grouped into three blocks for an easier understanding, as shown in Fig. 1.2. The first block contains the background and knowledge required to understand the rest of the thesis. This block is composed of two chapters. Chapter 1 is an introduction to the thesis, detailing the motivation behind the research and setting out the objectives to be addressed. Chapter 2 provides a review of the theoretical concepts used in this thesis. In this chapter, first the mobile technologies used in this thesis are presented: LTE and 5G. For each of these technologies, their main characteristics are described, with emphasis on the novelties provided by 5G. Next, an overview of MC in mobile networks is provided, presenting the different schemes studied in the literature and providing a vision of the main challenges of this functionality. Finally, an introduction to the SON paradigm is given, focusing on self-optimization.

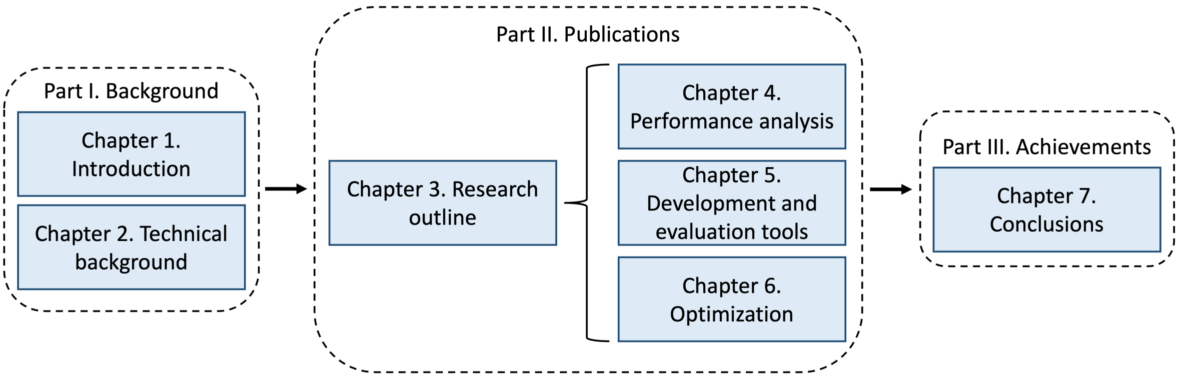


Figure 1.2: Document structure.

The second block corresponds to the publications that support this thesis. These are grouped in chapters according to their topic. In addition to the chapters corresponding to the publications, this second block includes a first chapter (Chapter 3) as a guide detailing the relationship between the publications and the challenges, objectives and chapters of this thesis. The research methodology followed during the development of the thesis is also presented in this third chapter, indicating the technologies and tools employed. The rest of the chapters included in this second block are directly related to the objectives established in the Section 1.2. Each of the publications included in these chapters illustrates the specific problem to be solved, making a detailed review of the state of the art, the proposed solution, and the evaluation of the results obtained.

Chapter 4 contains the results of the tasks of studying the characteristics and requirements of the networks and the environment. These tasks are performed prior to the development of optimization algorithms to obtain a better knowledge of the scenario. This chapter includes two papers related to Obj. 1 and 2 of this thesis. Specifically, the first paper addresses the digitization of the construction sector through the use of 5G technology. The second paper propose an anomaly detection framework able to detect different types of anomalies in KPIs of distinct nature.

Chapter 5 covers those works related to the development of frameworks that aims at improving the performance and the evaluation of the optimization algorithms. This chapter is related to Obj. 3 and 4 of this thesis and includes two papers. The first paper proposes a forecasting framework able to perform accurate predictions. To that end, this framework includes a feature selection phase prior to the prediction. The second paper presents a method for network modeling from the UE perspective. This method is able to automatically set up a testbed so that the UE perception of the test network is equal to that experience by an UE in a real network.

Chapter 6 is related to the development of self-optimization algorithms. In this way, this chapter is associated with Obj. 5, 6, 7 and 8 of this thesis. Chapter 6 includes three papers. The first paper presents an study on the impact of the RLC layer configuration in the QoE perceived by the users of different services in a mobile network. The results of this paper serves as a groundwork for the development of an optimization algorithm based on the adjustment of RLC to maximized the users' QoE. This optimization algorithm is presented in the second paper included in this chapter. The third paper proposes a proactive MC activation algorithm that aims at ensuring the communications requirements of the AGVs deployed in an industrial environment.

Finally, the third block consists in Chapter 7. This chapter presents an overview of the main results and conclusion of this thesis. Moreover, some of the main future lines of research are discussed.

This document also includes an Appendix A in which a brief summary in Spanish is provided.

Chapter 2

Technical background

This chapter provides a review of the technical background necessary to follow the content of this thesis. First, Section 2.1 presents the cellular technologies considered in the thesis: LTE and 5G, with special emphasis on their architectures, their main functions, and their differences. Next, Section 2.2 describes the main mobile networks MC techniques, and concludes by providing an overview of the current state of MC in 5G, highlighting the main benefits and challenges of using these techniques. Finally, Section 2.3 presents the SON concept, being this thesis especially focused on self-optimization.

2.1 Cellular technologies

This section aims to provide an overview of the cellular technologies that are the basis of this thesis. Section 2.1.1 describes LTE networks, which are currently the most advanced in their commercial deployment. Section 2.1.2 describes the 5G networks as an evolution of LTE. These networks have recently been commercially deployed in some countries.

2.1.1 LTE

Evolved Packet System (EPS), also known as LTE [101], is a mobile communications standard first proposed by the 3GPP in Release 8. This technology is characterized by the use of packet-switched networks for the delivery of all services, including voice (voice over IP, VoIP). In LTE, the downlink multiple access technique used is the Orthogonal

Frequency-Division Multiple Access (OFDMA), while the uplink uses Single Carrier Frequency Division Multiple Access (SC-FDMA), which is a variation of the previous technique. The use of these techniques allows LTE to reduce latency and increase data rates compared to previous cellular technologies. Despite its improvements over previous generations, it was not until the launch of LTE Advanced (LTE-A) in Release 10 that the standard met the requirements of a 4G technology.

Network architecture

The LTE network architecture consists of the evolved universal terrestrial radio access network (E-UTRAN) and the evolved packet core (EPC) (see Fig. 2.1) [102]. The EPC is the part of the network in charge of user mobility management, access control, and connecting to external networks. The EPC is composed of the following elements:

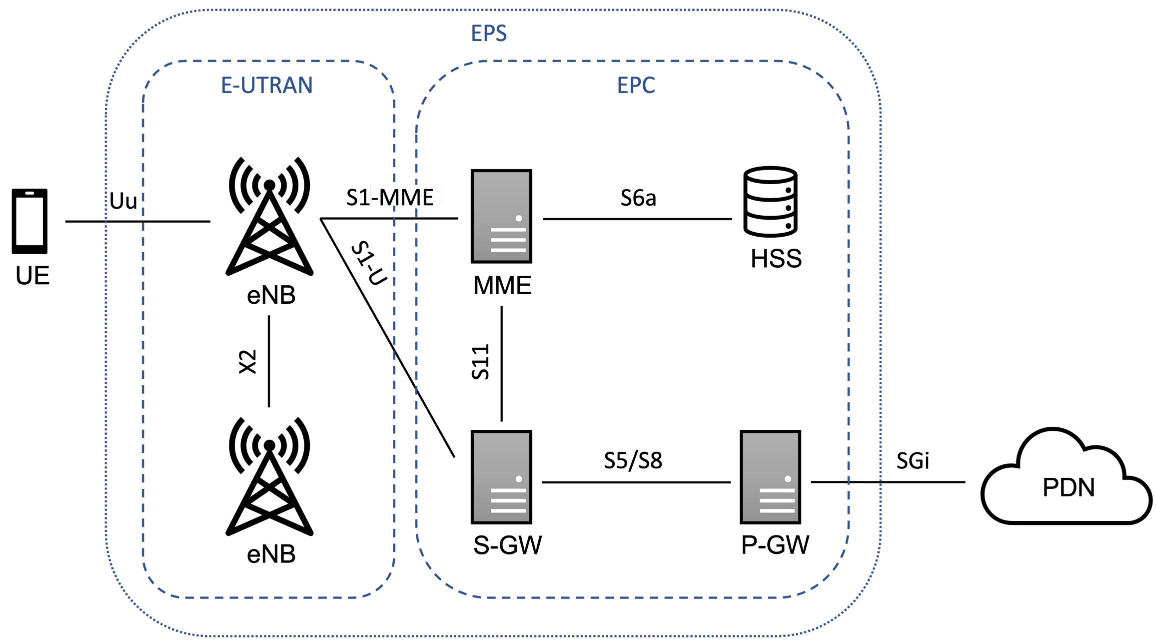


Figure 2.1: LTE architecture.

- Mobility management entity (MME). This element manages the control plane between the EPC and UE. Its main functions are:
  - Non-access stratum (NAS) signaling and NAS signaling security.
  - Access stratum (AS) security control.
  - Idle state mobility handling.
  - EPS bearer control.

- Serving gateway (S-GW). This element is in charge of connecting the user plane between the E-UTRAN and the EPC. Specifically, the MME has the following functions:
  - Anchor point for mobility between LTE cells and cells from other 3GPP technologies.
  - Termination of user plane for paging.
  - Packet forwarding, routing and buffering of downlink data for UEs in idle state.
- Packet data network (PDN) gateway (P-GW). This element is the connection point between the LTE network and other Internet protocol (IP) networks. The P-GW is responsible for:
  - Anchor point for mobility between 3GPP and non-3GPP access networks.
  - Policy enforcement features.
  - Charging support.
  - UE's IP address allocation.
- Home subscriber server (HSS). This is database that contains subscriber-related information. Its main functions are:
  - Mobility management.
  - Call and session establishment support.
  - Subscriber authentication.
  - Access authorization.

The E-UTRAN is the part of the network in charge of connecting UEs to the EPC. The E-UTRAN is composed of a single element called evolved node B (eNodeB or eNB). The eNBs main functions are:

- Radio resource management (RRM).
- Selection of MME at UE attachment.
- IP header compression and encryption.
- Routing of user plane data towards the S-GW.

- Measurement configuration for mobility and scheduling functions.
- Scheduling and transmission of paging messages and information broadcast.
- Radio interface measurement making (uplink direction).

Protocol stack

The transmission of information between the elements of the LTE network is done through the use of a protocol stack. The protocol stack used for the user plane (see Fig. 2.2) is different from the one used for the control plane (see Fig. 2.3). A brief description of the Uu interface protocols at the user plane is provided below. As can be seen in Fig. 2.3, some of these protocols are also used at the control plane:

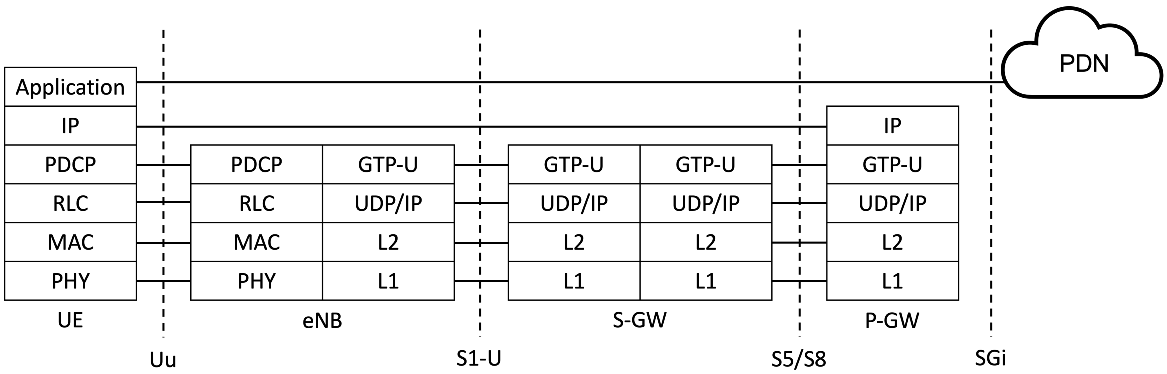


Figure 2.2: LTE protocol stack - User plane.

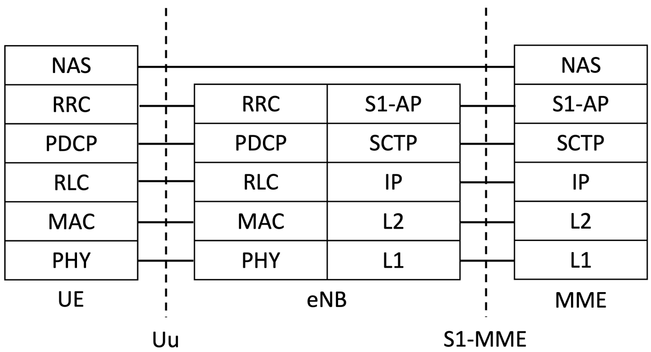


Figure 2.3: LTE protocol stack - Control plane.

- Physical (PHY). The physical layer is responsible for the actual transmission over the radio channel. It performs channel coding, modulation, processing functions associated with multiple transmit and receive antenna techniques and signal mapping to the appropriate physical frequency-time resources.

- MAC. The main function of this layer is the allocation of radio resources, although it also performs functions such as error correction through the use of the hybrid automatic repeat request (HARQ) algorithm, or the management of priority between different data streams from the same user and between different users.
- RLC. The purpose of the RLC layer is to provide an available radio link, providing a sequential delivery of packets and performing error detection. RLC functions include packet segmentation and reassembly. Further details of this protocol can be found in Chapter 6.
- Packet data coverage protocol (PDCP). This layer provides functions such as packet header compression and decompression, sequential delivery, duplicate detection, and packet encryption and decryption.
- Internet protocol (IP). IP is a network protocol that allows bidirectional data transfer.

The remaining Uu interface protocols used in the control plane are:

- Radio resource control (RRC). RRC controls other protocols. The main functions of this protocol include the sending of paging messages to users, cell selection procedures, the establishment and release of RLC connections, security and encryption control, user action reporting, mobility functions, etc.
- NAS. This protocol supports the mobility of UEs, as well as the session management processes for establishing and maintaining IP connections between the UE and the P-GW.

Radio access

The physical layer of LTE makes use of two multiple access technologies over the air interface: OFDMA in downlink and SC-FDMA in uplink (see Fig.2.4). OFDMA is a multi-user version of orthogonal frequency division multiplexing (OFDM). It is used to allow a set of users to share the spectrum of a certain channel. Multiple access is achieved by dividing the channel into a set of narrow subcarriers that are divided into groups according to the needs of each user. OFDMA allows multiple users to transmit on different subcarriers for each symbol. In downlink each subcarrier is modulated using from quadrature phase-shift keying (QPSK) to 256 quadrature amplitude modulation (QAM) [103]. Although OFDMA achieves high spectral efficiency, the combination of a high number of subcarriers results in a high peak-to-average power ratio (PAPR), which in turn causes radio transceivers to have high power consumption. Thus, in the uplink, the use of OFDMA causes an increase in UEs power consumption, which is unacceptable in mobile environments. For this reason, OFDMA is not considered as a suitable multiple access technology in uplink, and instead, the use of SC-FDMA is proposed. SC-FDMA utilizes a single-carrier transmitting signal, transmitting the data symbols in series over one wideband signal, with higher rate and more bandwidth than OFDMA. While in OFDMA each subcarrier transports an independent data stream, in SC-FDMA, each symbol expands for all the assigned subcarriers. The modulation schemes used in uplink range from $\pi/2$-binary phase-shift keying (BPSK) to 256 QAM [103].

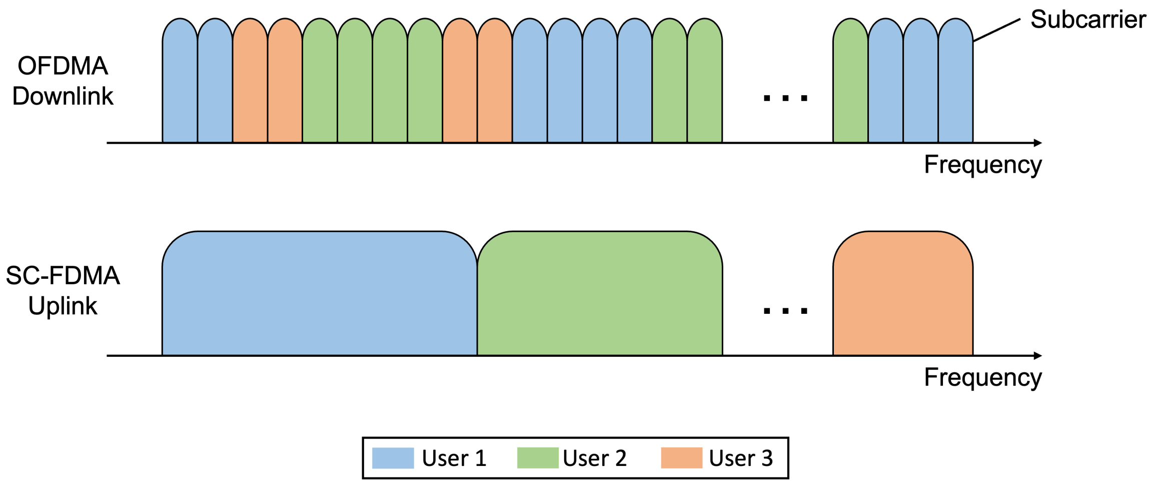


Figure 2.4: LTE multiple access technologies.

The system bandwidth values available in LTE are: 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz and 20 MHz. The smallest resource unit in the LTE physical layer is the resource element (RE), which consists of an OFDMA (downlink) or SC-FDMA (uplink) symbol in the time domain and a subcarrier in the frequency domain. For data transmission, the REs are organized into physical resource blocks (PRBs) which are the smallest unit that can be programmed in both uplink and downlink. A PRB consists of 0.5 ms (1 slot) in the time domain and 180 kHz in the frequency domain. On the one hand, depending on the spacing between subcarriers, the number of subcarriers in a PRB varies, being the most common case the use of 12 subcarriers of 15 kHz each per PRB. On the other hand, the number of symbols per PRB varies depending on the length of the cyclic prefix used, being the usual case the use of 7 symbols per time slot. In addition to user data, a PRB also contains reference signals and other control data.

In LTE, to increase network capacity and coverage, the use of multiple-input multiple-output (MIMO) technique is proposed. MIMO is a multi-antenna technique that allows the simultaneous transmission of multiple data streams at the same frequency and time, thus taking advantage of different radio channel paths and further improving spectral efficiency.

2.1.2 5G

5G networks are emerging as an evolution of 4G networks that aim to provide coverage for a wide variety of services that will benefit the economy and society as a whole. These services are classified into three categories according to their requirements [1,2]. The first category of services refers to eMBB communications, which present very high data rates requirements. This category encompasses human-centric use cases such as multi-media content or data services. The next category corresponds to URLLC, which comprises services that demand high reliability and low latency in their connections. Some examples include remote medical surgery, self-driving car or industry automation. The third category is mMTC, which are characterized by serving a large number of devices with low bandwidth requirements. This technology focuses on non-critical applications associated with smart buildings or smart cities, among others.

To meet the needs of this wide range of services, new functionalities have been introduced in 5G. Some of the most relevant are:

- Network slicing. This concept refers to the division of the physical network into multiple logical network known as slices. The slices are independently configured to optimally serve a particular type of application. The basic technologies for the implementation of network slicing are software-defined networking (SDN) and network function virtualization (NFV).
- Massive MIMO. This functionality is an extension of the MIMO proposed in LTE, in which the number of antennas used for the simultaneous transmission of data streams is increased. Thus, with massive MIMO it is possible to further enhance network capacity without the need to extend the frequency spectrum used.
- Beamforming. This technique is based on adjusting the amplitudes and phases

Table 2.1: 5G numerology configurations.

Numerology	Subcarrier spacing (kHz)	Cyclic prefix	Symbols per slot	Slots per subframe
0	15	Normal	14	1
1	30	Normal	14	2
2	60	Normal/Extended	14	4
3	120	Normal	14	8
4	240	Normal	14	16
5	480	Normal	14	32
6	960	Normal	14	64

of the signals that are transmitted/received through different antennas, so that a strong beam is formed towards the direction of interest, while minimizing interference.

- Numerology. Unlike in LTE, in 5G the subcarrier spacing and symbol duration are not fixed. Thus, 3GPP contemplates seven different configurations [104]. These configurations are shown in the Table 2.1.
- Frequency bands. In 5G, the use of three frequency bands is considered. First, the low-band spectrum includes those carriers below 1 GHz, which offer wide coverage but with limited maximum transmission data rates. Second, the mid-band spectrum consists of carriers between 1 GHz and 6 GHz. Finally, the high band spectrum, or millimeter wave (mmWaves), corresponds to carriers above 6 GHz. This band offers the highest data rates at the cost of lower coverage.
- MC. This functionality refers to the use of multiple wireless links between the UE and the network. These links can be established with different nodes of the network, with different component carriers (CC) of the same node, or with combinations of both. These links may be used to transmit different information, thereby increasing throughput, or to transmit replicated information, thereby improving reliability. More detail on this functionality is provided in Section 2.2.

Network architecture

The first standardization of 5G technology was proposed by the 3GPP in Release 15 [105], which defines two deployment options for 5G networks. On the one hand, a non-standalone 5G network (5G NSA) is considered (see Fig. 2.5). In this option, the use of the 5G radio interface known as new radio (NR) is combined with the infrastructure of LTE networks. This network deployment provides the same services as LTE but with improvements in terms of latency and throughput. In the other hand, the second option considers the 5G stand-alone architecture (5G SA) (see Fig. 2.6) that makes use of the 5G system (5GS). The 5GS is composed of the next-generation radio access network (NG-RAN) and the 5G core network (5GC). In this second option, the different services defined for 5G networks are offered. The new elements defined in 5G are described below [106, 107]:

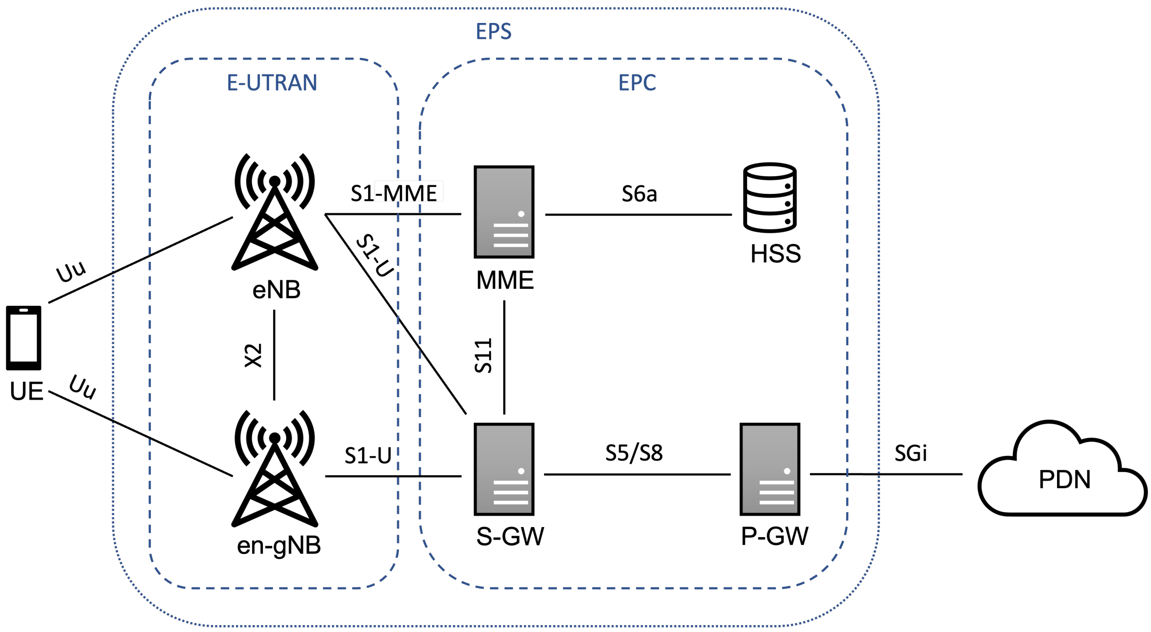


Figure 2.5: 5G NSA architecture.

- en-gNB. Network node that provides NR user and control planes to the UE and that is use as secondary node (SN) in E-UTRAN-NR dual-connectivity (EN-DC).

- ng-eNB. Network node that provides E-UTRAN user and control planes to the UE and that is connected to the 5GC.

- gNB. Network node that provides NR user and control planes to the UE and that is connected to the 5GC. The gNB and ng-eNB main functionalities are:

  - RRM functions such as radio bearer control (RBC), radio admission control (RAC), connection mobility control (CMC) and dynamic allocation of resources to the UE.

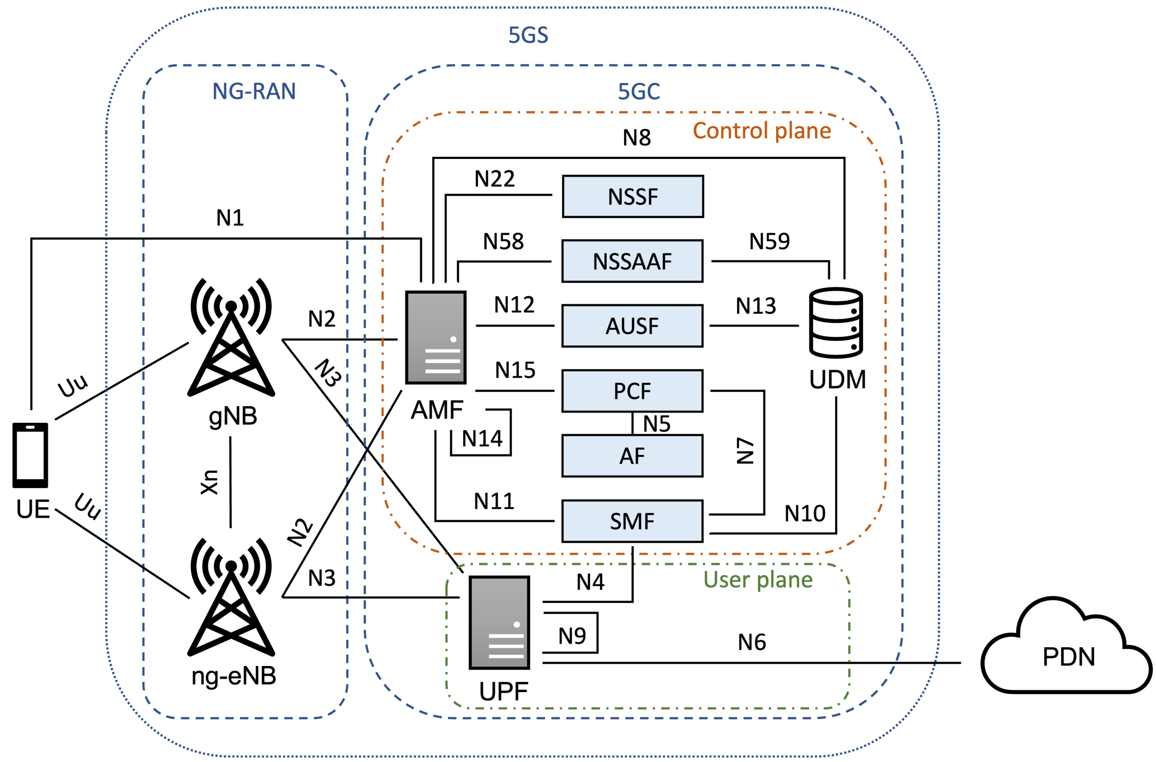


Figure 2.6: 5G SA architecture.

- IP header compression and encryption.
- Selection of AMF at UE attachment.
- Routing of user plane data towards the UPF and the control plane information towards the AMF.
- Scheduling and transmission of paging messages and information broadcast.
- Network slicing support.
- Quality of service (QoS) management.
- Measurement reporting for mobility and scheduling functions.
- Dual-connectivity.

• Access and mobility management function (AMF). This element is in charge of connection and mobility management tasks. Its main functions are:

  - NAS signaling security and termination.
  - AS security control.
  - Signaling between core network (CN) nodes for mobility between 3GPP access networks and supporting intra-system and inter-system mobility.

  - Access authentication and authorization.
  - Network slicing support.
  - SMF selection.

- User Plane Function (UPF). This element is in charge of connecting the user plane between the NG-RAN and the 5GC. The UPF has the following functions:
  - Anchor point for intra- and inter-radio access technology (RAT) mobility.
  - Packet inspection, routing, and forwarding.
  - User plane part of policy rule enforcement.
  - Traffic usage reporting.
  - QoS handling for user plane.

- Session management function (SMF). The main functionalities of this element are:
  - Session management.
  - UE IP address allocation and management.
  - Configuration of traffic steering at UPF.
  - Control plane part of policy rule enforcement and QoS.

- Policy control function (PCF). Some of the main functions of the PCF are:
  - Supporting unified policy framework.
  - Providing policy rules to control plane functions.

- Application function (AF). The AF provide services such as application influence on traffic routing or interaction with policy framework for policy control.

- Unified data management (UDM). This element includes the following functions:
  - Generation of 3GPP authentication credentials.
  - User identification handling.
  - Access authorization.
  - Support to service continuity.
  - Subscription management.

- Authentication server function (AUSF). The AUSF acts as an authentication server.
- Network slice selection function (NSSF). This element selects the set of network slice instances that serves the UE.
- Network slice specific authentication and authorization function (NSSAAF). This element supports for Network Slice-Specific Authentication and Authorization

2.2 Multi connectivity

MC is presented as one of the key functionalities of 5G. As previously mentioned, in its broadest sense, MC refers to the simultaneous establishment of multiple wireless links between the UE and the network. Thus, MC can be understood as an extension of two functionalities already introduced in LTE: carrier aggregation (CA) and dual connectivity (DC).

2.2.1 Carrier aggregation

CA was first introduced by the 3GPP in Release 10. This functionality refers to the aggregation of several CC from a single network node in order to obtain a wider transmission bandwidth (up to 640MHz) [101]. Depending on the frequency of the aggregated CCs there are three different CA modes: 1) inter-band contiguous, in which the aggregated CCs belong to the same frequency band and are also contiguous; 2) inter-band non-contiguous, in which the aggregated CCs belong to the same frequency band but are not contiguous; 3) intra-band non-contiguous, in which the CCs belong to different frequency bands. The bandwidth of the aggregated CCs and the number of CCs used in downlink and uplink can be different.

When CA is used, the UE has a number of serving cells, one for each CC. However, only one RRC connection is available and is managed by one cell, called the primary cell (PCell). The remaining cells are referred to as secondary cells (SCells). The SCells are added and removed as needed, while the PCell is only changed with a HO procedure. Fig. 2.7 shows a high-level diagram of a typical CA scenario, where an UE is connected to two cells in the same eNB.

In CA, user traffic is split between CCs in the MAC layer that must be able to to handle scheduling on a number of CCs. An HARQ entity is required for each serving

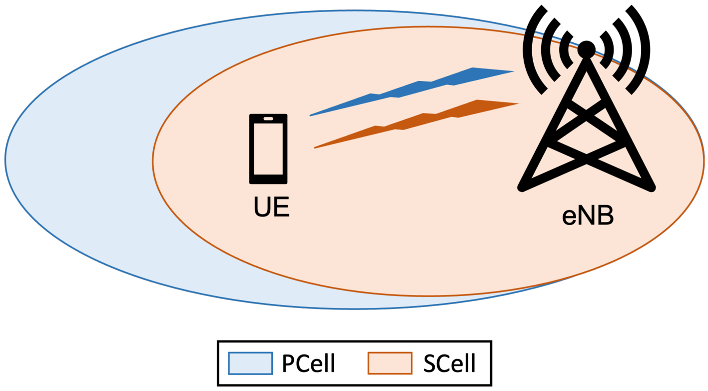


Figure 2.7: High-level CA diagram.

cell. Moreover, a transport block (TB) is generated per transmission time interval (TTI) and per each serving cell in the absence of spatial multiplexing. Fig. 2.8 shows the main changes introduced by CA in the LTE radio interface protocols.

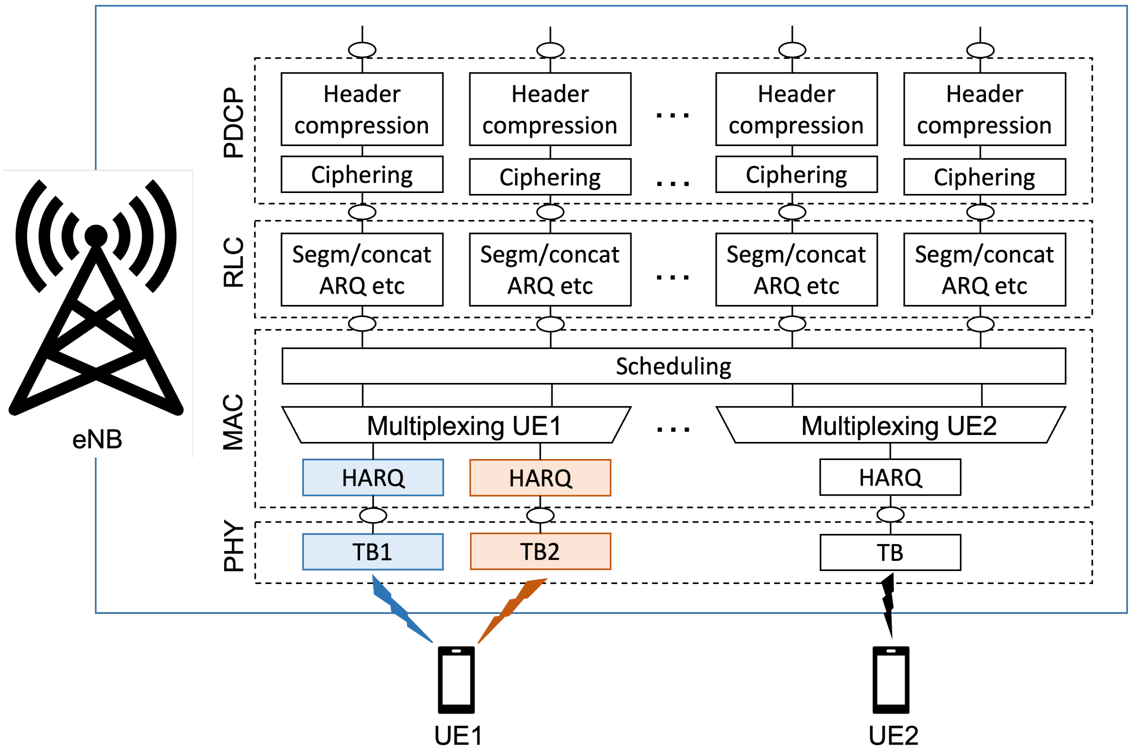


Figure 2.8: Layer 2 structure for CA in LTE.

In order to support the use of CA in heterogeneous networks, the 3GPP introduced the concept of inter-site CA in Release 11. In inter-site CA the PCell and the SCells are not located in the same network node, providing more flexibility than the traditional CA scenario. In this sense, inter-site CA could be considered as a type of DC [108]. In CA scheduling decisions are taken jointly for all the cells implying very tight coordination. Thus, the node providing the SCell to the UE must be a remote radio head (RRH) with an ideal backhaul connection (high bandwidth, low latency fibers) to the eNB responsible of making the scheduling tasks. Fig. 2.9 shows a high-level diagram of a typical inter-site CA scenario, where an UE is connected to two cells: a PCell, provided by an eNB and an SCell, provided by a RRH.

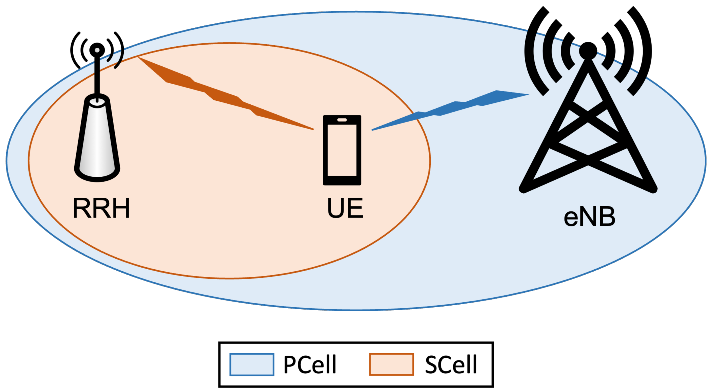


Figure 2.9: Inter-site carrier aggregation.

2.2.2 Dual connectivity

DC was first introduced by the 3GPP in Release 12. This functionality can be seen as an extension of inter-site CA for the case of a non-ideal backhaul, aggregating CCs from two different eNBs. One of these nodes takes the role of master node (MeNB) and the other of secondary node (SeNB) 2.10. The MeNB is responsible for carrying signaling between the E-UTRAN and the EPC, managing the DC configuration, and holding the PCell. DC signaling between the MeNB and the SeNB is performed by means of the X2 interface. The user plane data is transmitted from/to the UE to/from both nodes. To this end, the 3GPP propose two user plane architectures. In the first architecture (see Fig. 2.11a) the user plane data is split in the MeNB. In this architecture the user plane data is transferred from the MeNB to the SeNB through the X2 interface. In the second architecture (see Fig. 2.11b) both MeNB and SeNB have a user plane connection to the S-GW.

To implement DC, two radio bearer types has been defined: direct bearers, and split bearers. While a direct bearer uses radio resources from one eNB, a split bearer uses radio resources from both the MeB and the SeNB. The direct bearers are divided in master cell group (MCG) and secondary cell group (SCG), depending on which node (MeNB and SeNB) they are located. The signaling radio bearers (SRBs) are always

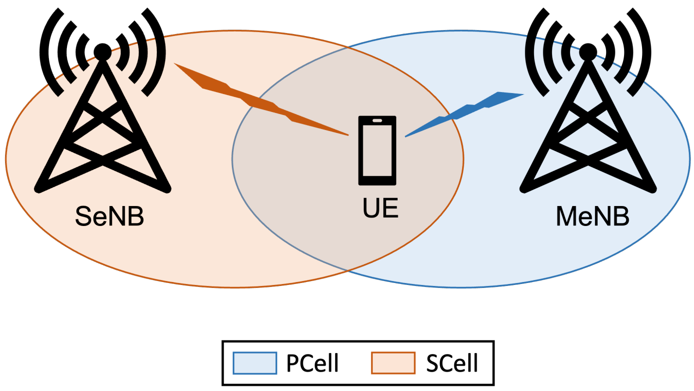
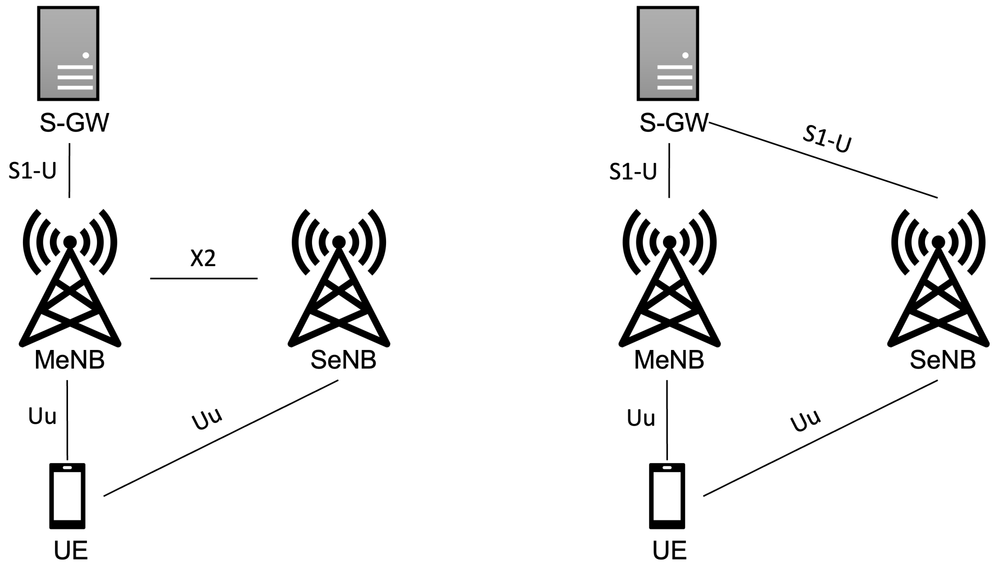


Figure 2.10: Dual connectivity.



(a) User plane split in the MeNB.

(b) User plane split in the CN.

Figure 2.11: DC user plane architectures.

configured as MCG bearers. On the other hand, the data radio bearers (DRBs) may be configured as MCG, SCG or split bearers. Unlike in CA, in DC the division of user traffic is done at the PDCP layer. Fig. 2.12 shows the structure of the layer 2 for DC in LTE.

2.2.3 Multi connectivity in 5G: benefits and challenges

The first phase of 5G deployment consists of the 5G NSA architecture. Thus, in Release 15, the 3GPP defines the multi-radio DC (MR-DC) as an extension of the extinct DC in LTE [109]. In MR-DC the UE utilize resources provided by two different nodes, a eNB and a gNB, connected by means of a non-ideal backhaul. One of the nodes takes

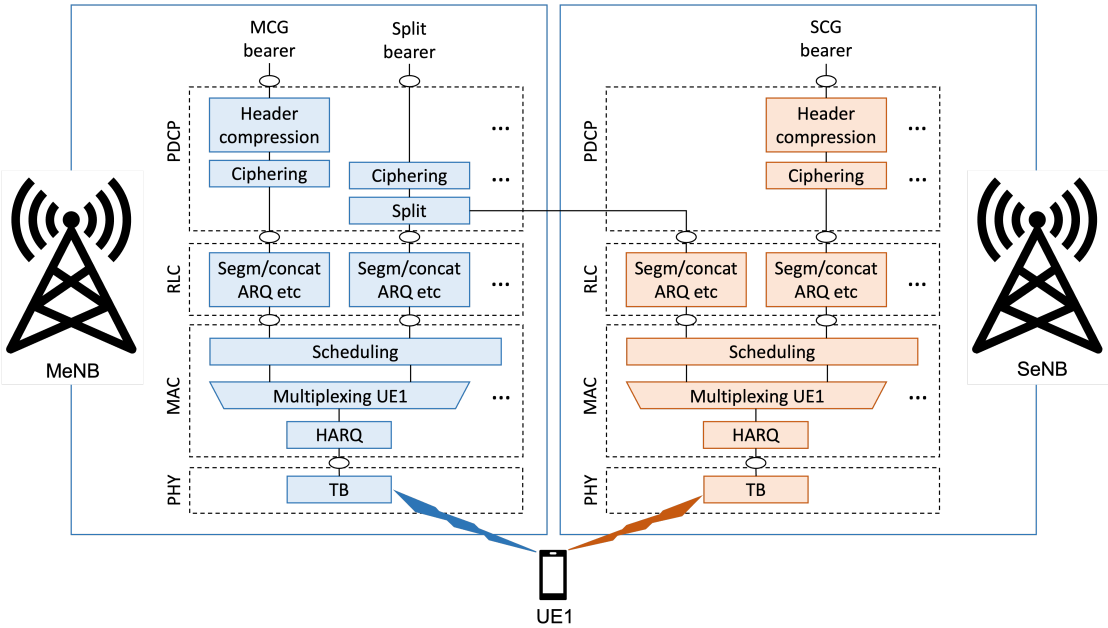


Figure 2.12: Layer 2 structure for DC in LTE.

the role of master node (MN), carrying the signaling between the UE and the CN, and the other node takes the role of SN.

Nowadays, the 3GPP contemplates the establishment of DC using two gNBs, called NR-NR DC (NR-DC), thus providing coverage for MC is 5G SA scenarios. However only the aggregation of resources of up to a maximum of two nodes is considered. In this sense, it is expected that future releases will includes the aggregation of more nodes.

During the last few years, several research works have demonstrated the benefits of different MC techniques, including [110]: 1) improved mobility robustness, reducing the interruption time and the signaling required for a HO; 2) improved reliability, sending duplicated data over different links and therefore, reducing packet loss rates; 3) improved data rate, combining multiple data streams from different nodes into a single data stream; 4) service segregation, allowing to segregate services with distinct requirements through different communication paths.

Despite the benefits of MC, it is important to be aware of its limitations, as well as the challenges associated with its implementation and use. Some of the main MC-related challenges to be addressed by the research community are [110]:

- Packet reordering. In MC, due to different radio link conditions, radio access technology (RAT) procedures, and path delays, the packets may arrive out of order. To cope with this issue, in [111] the 3GPP defines a reordering method for DC and MR-DC based on the use of a static reordering timeout. The value of this reordering timeout should be carefully chosen in order to not degrade the performance of time-sensitive applications.

- Flow control. To avoid under- or over-utilized links and, therefore, poor overall system performance, the use of a dynamic flow control, that considers aspects such as radio link conditions, QoS requirements, or backhaul latency, is needed.

- MC operation management. Uncontrolled use of MC may lead to network problems, such as reduced network capacity, inefficient use of radio resources, increased power usage on the UE side, or increased uplink interference. Thus, the decision of when to activate MC and which nodes and CCs should be used is of a great importance.

- Usage of more than two nodes. As mentioned above, the standard currently only covers the use of a maximum of two nodes in MC. The use of more nodes will allow the aggregation of resources even if one of the nodes fails. However, the use of more nodes will also increase the complexity of MC implementation and management.

2.3 Self-organizing networks

Mobile networks are constantly evolving. To meet the ever-increasing user demands, mobile technologies include increasingly more new functionalities and services which increase the complexity of managing and maintaining these networks. In order to save CAPEX and OPEX, MNOs have focused their attention on automating traditional tasks, introducing the concept of SON. Specifically, the main objectives of SON are:

- To reduce of installation cost and time.

- To reduce of OPEX by decreasing manual efforts when designing, installing, maintaining, optimizing, diagnosing, and healing the network.

- To reduce the CAPEX by efficiently using the network infrastructure and spectrum resources.

- To improve user experience and service quality.

- To improve network performance.

To meet these objectives, different SON algorithms are used, each of these algorithms being focused on performing a certain task. The execution of SON algorithms follow the next phases:

- Data collection. This phase encompasses the tasks of network information and measurements gathering. The typical sources of information are [112]:
  - Configuration management parameters (CMs). These parameters collect information on the current configuration of the network elements.
  - Performance management parameters (PMs). These parameters gather information about the number of times a certain event takes place in the network during a period of time. They reflect the performance of the network elements.
  - Alarms. Alarms are messages triggered by the network elements in response to a network malfunction.
  - KPIs. These indicators provide a meaningful performance measure. They are calculated as a combination of other parameters, e.g., applying some formula to several counters.
  - Drive test. These metrics refer to field measurements of network performance made by specialized UE moving through a given area.
  - Mobile traces. Mobile traces store information about the events generated by a given UE. These events are collected by a network element.
  - Context information. Context information refers to information about the environment in which the network is located, e.g., information about the weather, location of users, type of scenario, etc. This information is external to the network and is not collected by the network elements, but impacts its performance.
- Data analysis. During this phase the current status of the network is identified.
- Decision-making process. In this phase, the actions to be performed based on the current status of the network are determined.
- Actions execution. This is the final phase, in it the selected actions are carried out.

Depending on network element in which the SON algorithm is executed, three different architectures can be distinguished: 1) centralized, in this architecture SON algorithms are executed in a central network management entity, having access to data from all network elements; 2) distributed, in this case the SON algorithms run on the network nodes (i.e., eNB or gNB), experiencing shorter execution time but usually having access only to the data collected by one node; 3) hybrid, this architecture executes some algorithms in the network node and others in the central entity depending on its requirements in terms of data and execution time.

According to the 3GPP [7] SON algorithms are categorized into three groups:

- Self-configuration. This process consists of configuring through automatic installation procedures the new nodes deployed in the network. To this end, self-configuration establishes the basic parameters and downloads the software required for the operation of the deployed node. Moreover, this process performs periodic updates of the software.
- Self-optimization. The self-optimization process takes place when the network is in operation. This process consists of performing network auto-tuning tasks based on the measurements reported by users and network nodes. The objective of self-optimization is to reconfigure different network parameters to achieve an optimal performance.
- Self-healing. This process is based on the analysis of alarms and other information collected by the network to detect network failures, determine the cause of the failure and initiate temporary actions to recover from the failure. Self-healing also monitors the execution of the actions and decides the next step accordingly.

This thesis is focused on self-optimization algorithms.

2.3.1 Self-optimization overview

As mentioned above, self-optimization is the process of automatically adjusting network configuration parameters to obtain the best possible network performance. Among the main use cases associated with self-optimization, the following functions can be found [8]:

- Coverage and capacity optimization. A fundamental task during network operation is the optimization of coverage and capacity. The main objective of coverage optimization is to be able to provide users with connections at an acceptable quality according to the operator's policies throughout the area where the network operates. In this way, coverage is intended to be continuous, so that users do not perceive cell edges. Coverage optimization has a higher priority than capacity optimization. However, as coverage and capacity are related, it is important to reach a trade-off between both of them.

- Energy savings. Energy expenses are one of the main costs incurred by operators. In order to save energy, it is important that the network capacity is adjusted to the real traffic demands at any given moment. The goal of energy saving is to maintain an adequate capacity level while saving energy by switching off unneeded cells.
- Interference reduction. This function focuses on reducing the interference levels of the network by switching off unneeded cells.
- Mobility robustness optimization. This function focuses on the correct configuration of HO parameters. Misconfiguration of these parameters leads to poor user experience and also to a waste of network resources by causing HO ping-pongs, HO failures and radio link failures.
- Mobility load balancing optimization. This function performs an adjustment of the cell reselection/HO parameters so that the traffic load is evenly distributed among the cells, minimizing the number of HO and redirections required to achieve this load balance.

2.3.2 Self-optimization in 5G

The new services and features of mobile communications networks, as well as the increase in the size and complexity of network management and maintenance tasks, open up a new self-optimization paradigm in which new aspects should be considered. As a result, the management tasks of 5G networks includes new features that make them completely autonomous while providing optimal use of network resources. Some of the main features to consider for the development of optimization algorithms in 5G networks are:

- The use of big data techniques. In 5G networks, the number of data sources is expected to increase significantly. In addition to the increase in the volume and variety of data, it is expected that real-time information on the status of the networks will be available, thus increasing the velocity of this data. In order to handle all this huge amount of data efficiently, it is necessary to use advanced data processing techniques such as MapReduce [113]. MapReduce is a programming paradigm that supports parallel and distributed computing of large collections of data across clusters of computers.

- The use of dimensionality reduction techniques. To efficiently manage the data to be used as input to the different SON algorithms, thus ensuring optimal results the use of dimensionality reduction techniques are required. These techniques aim to reduce the number of dimensions, i.e., internal and external indicators, needed to represent the network state, without losing useful information and expressing the available information in a more efficient way. Dimensionality reduction techniques are classified into feature selection techniques and feature extraction techniques. On the one hand, the objective of feature selection techniques is to find the best subset of features from the original set, selecting those features most relevant to build the required model. On the other hand, feature extraction techniques generate new features from the combination of the features provided as input, thus reducing the final number of features to be taken into account to generate the model.

- A user-centric approach. To meet the increasingly demanding requirements of mobile network users, the approach to optimization techniques has been evolving. In this way, network management experts are now focusing their attention on QoE optimization.

- A proactive approach. Conventional network optimization algorithms focus on the use of reactive methods that initiate actions to readjust network configuration parameters when a performance degradation is detected. However, these algorithms cannot meet the requirements of new 5G services in terms of very low latency and high throughput. To satisfy these requirements, the use of proactive methods is proposed in the literature, leading to what is known as anticipatory networking. These methods are based on the use of predictive algorithms that analyze current and past events to anticipate the future state of the network.

- The use of artificial intelligence (AI) techniques. AI techniques are responsible for making machines and systems capable of imitating the cognitive functions associated with humans, such as perceiving, reasoning, learning or solving a problem.

These techniques include ML, DL and reinforcement learning (RL) algorithms that have proven to be effective for tasks such as identifying patterns, managing large amounts of data, adapting to changing environments, predicting or solving complex problems, improving the performance of other traditional solutions [114]. Thus, a growing number of researchers and network experts are proposing the use of AI techniques for the development of SON algorithms in the increasingly complex and demanding 5G networks [115–117].

Chapter 3

Research outline

This chapter is composed of two sections. Section 3.1 describes the papers that support this thesis, making an association between the papers and the objectives of the thesis. For each of the papers, their contributions to the state of the art are highlighted. Section 3.2 presents the research methodology used, presenting the tools, techniques and equipment used.

3.1 Description of the publications

This section presents the outcomes (research papers) arising from this thesis. These papers address the challenges and objectives established in Section 1.2. Fig. 3.1 shows the relationship between the challenges, the objectives and the outcomes to which they respond. In the figure, each paper is represented as an individual block, indicating in which chapter of this thesis the paper is included. The following subsections provide a summary of each of the papers that support this thesis.

3.1.1 5G for construction: Use cases and solutions [I] (Chapter 4.1)

The first work related with this thesis is included in Chapter 4, which covers all those tasks related to the study of the characteristics and requirements of the networks and their environments. Specifically, this paper outlines the benefits that the use of 5G technology could bring to the construction sector (Obj. 1). Despite being one of the largest sectors of industry, the construction sector is one of the sectors in which the

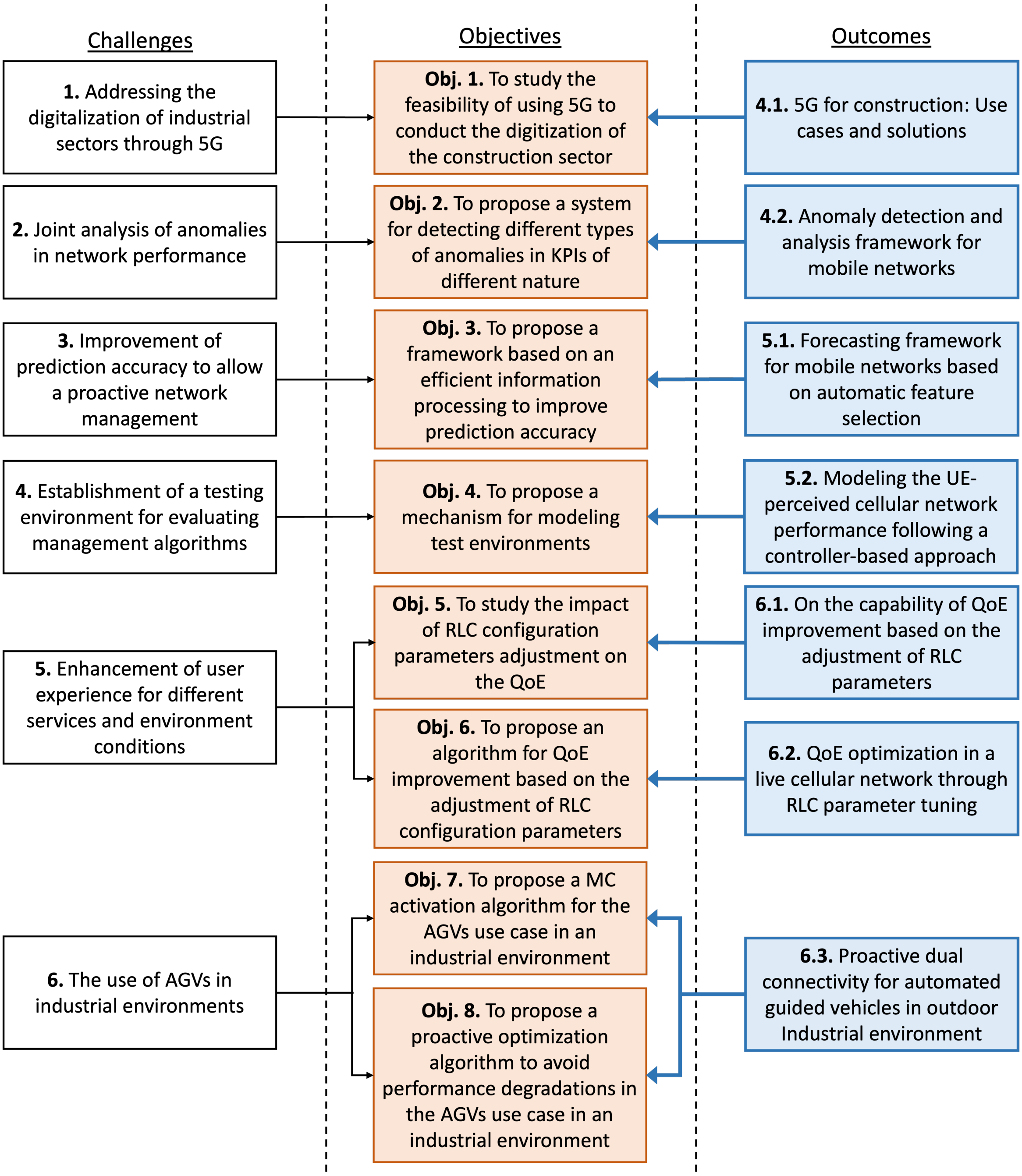


Figure 3.1: Challenges, objectives and outcomes.

impact of the fourth industrial revolution has been the smallest. This is due to the particular conditions of the sector, where most of the work is carried out on sites characterized by their dynamism, decentralization or temporary nature. Thus, the automation and digitization of this sector presents multiple challenges for the implementation of information and communications technologies (ICTs). This paper focuses on the challenges associated with the implementation of communication networks.

To cope with these goals, first, different use cases associated with the digitization of construction are defined, identifying the main challenges of each of them in relation to the use of communication technologies. Secondly, the main characteristics of 5G that would allow responding to the challenges previously highlighted are presented. Next, this paper proposes a high-level network architecture for the integration of 5G in the sector. Finally, the paper highlights the main lines of future work identified by the authors.

3.1.2 Anomaly detection and analysis framework for mobile networks [XI] (Chapter 4.2)

This section presents the second of the works carried out in relation to Chapter 4 of this thesis. In particular, this paper aims at proposing a holistic anomaly detection framework (Obj. 2). The proposed solution can detect both isolated or short-term anomalies and anomalies maintained over time in KPIs of different nature, performing the detection in either periodic and non-periodic KPIs. In addition, the framework allows the configuration of certain parameters by the operator or network administrator, thus taking into account the policies they use to determine whether the network behavior is acceptable or not. In this sense, this framework presents a complete analysis of anomalies found in a wide variety of KPIs, being very useful for performing tasks such as data labeling or detailed studies of network performance with the objective of developing fault management or network optimization algorithms.

In order to jointly analyze and perform detection on periodic and non-periodic KPIs, the framework incorporates a periodicity detection and elimination phase for those periodic KPIs. The detection of different types of anomalies is possible thanks to the use of two different detection algorithms that are used in parallel. On the one hand, a threshold-based detection algorithm is used for the detection of short-term anomalies. On the other hand, for the detection of long-term anomalies, a detection algorithm based on the signal change points is used. The results of these two algorithms are combined using the logical OR operation. Finally, using a weighting system based on the duration of the anomalies and the percentage of degradation of the KPIs during the anomalies, it is determined which of the detected anomalies are considered as degradations (severe anomalies).

Data from a commercial LTE-A network has been used to evaluate the framework. The results show that the framework can correctly detect the anomalies, achieving accuracy and precision results of 95.94% and 87.20% respectively.

3.1.3 Forecasting framework for mobile networks based on automatic feature selection [II] (Chapter 5.1)

Chapter 5 deals with the developments of frameworks and tools to improve the performance and the evaluation of optimization algorithms. The first paper included in this chapter addresses the use of data processing techniques prior to the development of optimization algorithms. The use of these techniques helps to improve the performance of management algorithms. Specifically, the objective of this paper is to propose a forecasting framework for the improvement of predictions accuracy (Obj. 3), leading the way for the subsequent development of anticipatory networking algorithms. To this end, the use of automatic feature selection techniques is proposed as a prior step to the prediction of network KPIs. The automatic feature selection proposed in this work is applied considering the two-dimension of KPIs: their type and their time dependence. Thus, the proposed solution selects which indicators and which time instants of each indicator are the most relevant for predicting a target KPI. The features selected are then used as input to a forecasting algorithm.

To evaluate the framework proposed, a dataset from a commercial LTE-A network has been used. Tests have been performed using three forecasting algorithm with different complexity: linear regression (LR), SVR and gated recurrent unit (GRU). Moreover, the impact of using the proposed framework to predict different lags in the future is analyzed. The performance of the proposed solution has been compared with two baselines: the use of the current sample of all KPIs to predict, and the use of all available information to predict. The results shows that the proposed framework improves the accuracy of the two baselines. In addition, thanks to the use of the two-dimensional automatic feature selection step it is possible to achieve with simple prediction techniques (LR and SVR) prediction results similar to those obtained with more complex prediction techniques (GRU).

3.1.4 Modeling the UE-perceived cellular network performance following a controller-based approach [III] (Chapter 5.2)

The second paper included in Chapter 5 addresses the problem of setting up test environments where it is possible to test algorithms before their implementation in commercial networks (Obj. 4). Running trials on a testbed allows detecting possible failures or bugs in the algorithms before their implementation on real networks, thus avoiding errors in the configuration of parameters that may lead to service degradations. Specifically, this paper proposes a mechanism to replicate the perception of the performance of commercial networks from the UE's point of view in a testbed, i.e., getting users connected to the testbed network to report the same values of UE performance indicators as UEs connected to the commercial network. The proposed mechanism allows modeling and optimizing independently different areas of the networks with different behaviors.

The modeling process consists of three steps. The first step is the execution of a measurement campaign in commercial networks. The second step consists of the identification of different patterns of behavior in the measured networks. For this purpose, a clustering of the data collected in the measurement campaign is performed. This clustering is performed based on the UEs' perception of the network behavior. These clusters are taken as input in the third step. The third step consists of adjusting the testbed configuration parameters to achieve a given behavior from the UE's point of view. For this purpose, the use of a controller based on the Taguchi method is proposed.

The measurement campaign used in this work has been carried out in commercial networks of different European operators. The testbed network used is a LTE picocell network deployed at the Telecommunication Engineering School of the University of Malaga, called UMAHetNet (see Chapter 5).

3.1.5 On the capability of QoE improvement based on the adjustment of RLC parameters [IV] (Chapter 6.1)

After completing the preliminary tasks included in Chapters 4 and 5, the problem of optimizing mobile networks is addressed. The optimization methods proposed in this thesis are presented in Chapter 6. The first paper included in chapter aims at assessing the impact of the adjustment of RLC layer configuration parameters on the QoE perceived by users (Obj. 5). This work extends the analysis carried out in the literature by performing a detailed analysis of the two modes of operation of the RLC layer: unacknowledged mode (UM) and acknowledged mode (AM), and the impact of the adjustment of the configuration parameters of these layers on the QoE.

To analyze the impact of RLC adjustment on QoE, two of the most commonly used services in a mobile network are used: real-time video streaming and file transfer. Due to their different requirements in terms of latency and throughput, these services make use of different RLC operation modes: RLC UM, in the case of the real-time video streaming service, and RLC AM, in the case of the file transfer service. First, the QoE perceived by users of a real-time video streaming service is analyzed in relation to the size of the RLC UM transmission buffer. The size of the RLC UM transmission buffer has a direct impact on packet loss and delay. Next, the QoE perceived by the users of a file transfer service is analyzed in relation to two of the RLC AM configuration parameters, the timers: t-PollRetransmit and t-StatusProhibit. A bad setting of these configuration parameters affects the delay experienced by the packets. Furthermore, these analysis are performed for different network load situations.

The study is carried out in an simulated LTE network, providing a range of optimal values for each of the configuration parameters used in the different situations tested. Thus, this paper lays the foundations for the development of a QoE optimization algorithm based on the adjustment of the RLC layer configuration parameters.

3.1.6 QoE optimization in a live cellular network through RLC parameter tuning [V] (Chapter 6.2)

This section presents the second of the works carried out in relation to Chapter 6. In particular, this paper proposes an algorithm to optimize the QoE of users in a mobile network (Obj. 6) by adjusting the configuration parameters of the RLC layer. Thus, this paper extends the work presented in [**IV**] where an analysis of the impact of the RLC layer adjustment on the QoE is performed.

The proposed optimization algorithm is a Taguchi-based controller similar to the one used in [**III**]. The main difference of the controllers used in these two works lies in the objective pursued in each of them. While in [**III**] the controller is used with the objective of achieving certain performance values, in this paper, the objective is to maximize the QoE perceived by the users. Moreover, unlike in **[III]**, in this paper the parameters modified by the controller are the RLC layer configuration parameters. This work covers both QoE optimization for users of a real-time video streaming service and for users of a file transfer service.

The evaluation of the algorithm has been carried out both in a simulated environment, where tests have been performed using scenarios with different load conditions, and in a real LTE testbed, the UMAHetNet.

3.1.7 Proactive dual connectivity for automated guided vehicles in outdoor industrial environment [VI] (Chapter 6.3)

The last paper included in Chapter 6 focuses on an Industry 4.0 environment. In this new industrial concept, 5G technology is presented as an enabling technology to meet the needs of new industrial applications. In particular, this paper addresses the use case of AGVs in an outdoor industrial environment that presents strict requirements in terms of high data rates in the uplink. To meet the communication needs of these AGVs, a system for proactive DC activation (Obj. 7 and 8) is proposed.

The proposed system is composed of two stages. In the first stage, QoS prediction is carried out. For this purpose, a prediction algorithm based on the combined use of clustering and logistic regression is used. In the second stage, decision making on DC activation or deactivation is carried out. This second stage implements a rule-based algorithm that makes use of the QoS prediction performed in the previous stage and the reference signal received power (RSRP) values recorded by the user for both the serving cell and the strongest neighboring cell.

The evaluation of the proposed method has been carried out in a simulated 5G environment making use of two different network deployments: a network with small cells in which all the cells make use of the same frequency spectrum, a network with macro and small cells in which the cells are divided into two layers (a macro cell layer and a small cell layer), each of these layers making use of a different part of the spectrum. In addition, the performance of the proposed system has been compared with two baselines. The results show that the proposed system is able to keep the DC activation errors that cause the unnecessary signaling overhead in the network to acceptable values. In addition, the proposed solution is more robust, being more resilient to changing radio environment and interference conditions compared to the baseline algorithms.

3.2 Research methodology

The studies conducted in this thesis have been carried out following a structured methodology composed of different stages. Fig. 3.2 shows the different stages of the methodology adopted in this thesis, which are described below:

- Background review. The first stage of the methodology consisted of an in-depth analysis of the performance of the mobile technologies used in this thesis (LTE and 5G) and the study of the state of the art, focusing on network optimization techniques. In this way, the main challenges to be addressed were established. During this phase, the characteristics and needs of new 5G scenarios and use cases were also studied, with special emphasis on Industry 4.0 environments.

- Problem formulation. In the second stage of the methodology, the problem formulation was carried out for each of the challenges identified in the previous stage. Thus, the issues to be investigated were defined in detail, and the approaches to solve them were planned.

- Data preparation. The third stage of the methodology consisted of collecting and pre-processing the data used to validate and evaluate the proposed solutions. Data from both real networks and simulated environments were used in this thesis. In addition, the use of data pre-processing techniques should be highlighted, being especially relevant when using real data.

  – Simulated data. For those cases where real network data were not available or a controlled environment was required for the validation and evaluation of the proposed systems, simulated data have been used. Specifically, two different network simulators have been used in this thesis. On the one hand, the LTE module of the ns-3 simulator called LENA [118] has been used. LENA is an open source LTE/EPC simulator. The simulator includes the E-UTRAN and the EPC. Some of the most important features of LENA are [119]: the granularity of the radio model (PRB); the implementation of the protocol stack in the data and control planes, which allows a correct

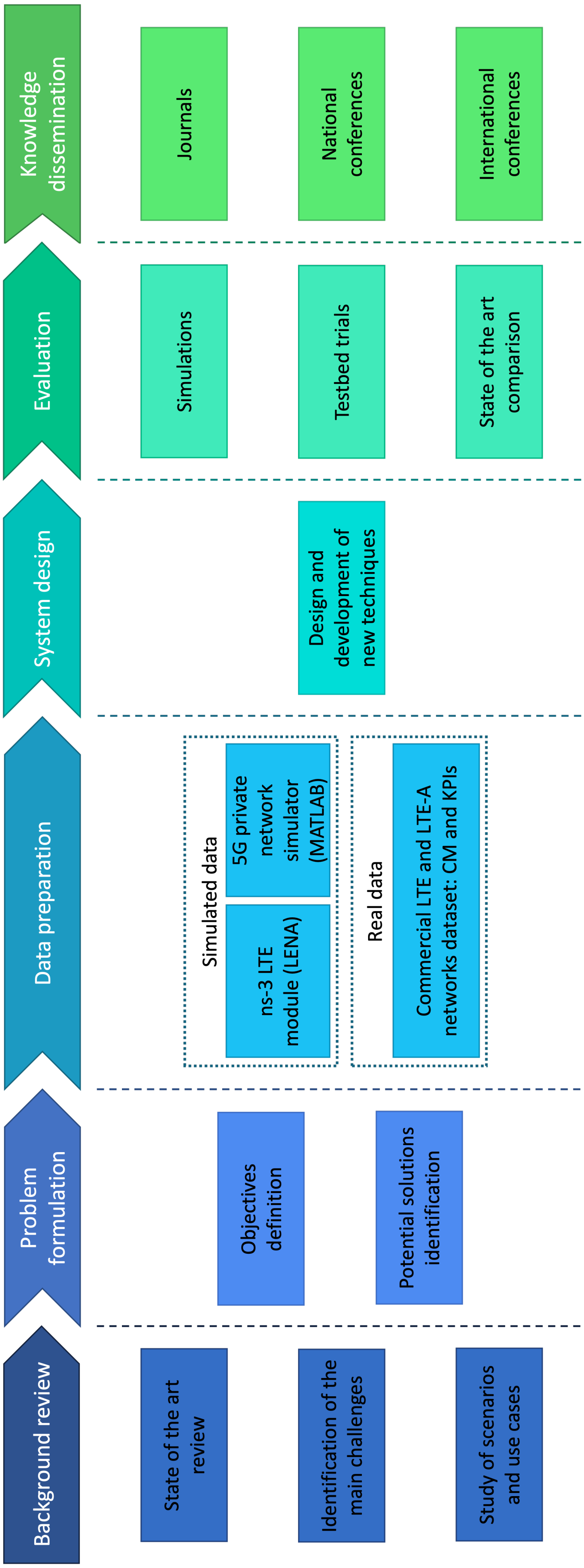


Figure 3.2: Research methodology.

interaction with IP networks and QoE evaluation; and the simplification of the EPC, simulating a single MME and S-GW and hosting the S-GW and the P-GW in the same node. On the other hand, a system-level simulator of a private 5G network in an outdoor industrial environment has been developed in the context of this thesis. This simulator is based on a real industrial scenario in which the deployment of a private 5G network composed of 9 cells implemented by RRHs and coordinated by the same gNB is proposed. The simulator is focused on the AGVs use case. A ray-tracing tool [120] has been used to compute the coupling gain values along the AGVs movement paths, and a urban traffic simulation tool [121] to simulate the physical movement of the AGVs. More details on the implementation of this simulator can be found in Chapter 6. This simulator has been coded in MATLAB.

  - Real data. For the development of this thesis, data from different commercial networks have been used. On the one hand, data collected in measurement campaigns carried out in LTE networks of several European operators in the framework of the MONROE project [122, 123] have been used. On the other hand, data from LTE-A networks provided by TUPL in the framework of the NEREA project have been used. Of the different types of data included in the datasets, CMs and KPIs have mainly used. Python libraries and tools such as scikit-learn, pandas or tensorFlow have been used for data pre-processing.

- System design. During this phase, systems and methodologies to overcome the identified challenges were designed and implemented. For this purpose, different techniques and algorithms were analyzed, using the best solution for each case.

- Evaluation. In this phase, the proposed systems were validated and evaluated. To this end, different types of tests have been used.

  - Simulations. Simulations encompass both those tests performed on the simulators described above and tests performed with real network data.
  - Testbed trials. These tests refer to the deployment of some of the proposed solutions in the UMAHetNet (see Chapter 5) for the evaluation of their performance.
  - State of the art comparison. Some of the proposed systems have been compared with solutions with the same purpose found in the literature, thus showing their benefits with respect to the state of the art.

- Knowledge dissemination. Finally, the most relevant results obtained during this thesis have been published in journals and presented at national and international conferences.

Chapter 4

Performance analysis

4.1 5G for Construction: Use Cases and Solutions

J. Mendoza, I. de-la-Bandera, C.S. Álvarez-Merino, E.J. Khatib, J. Alonso, S. Casalderrey-Díaz, and R. Barco, "5G for Construction: Use Cases and Solutions," *Electronics*, vol. 10, no. 14, p. 1713, Jul. 2021. DOI: 10.3390/electronics10141713.

Abstract: The world is currently undergoing a new industrial revolution characterized by the digitization and automation of industry through the use of Information and Communication Technologies (ICTs). The construction sector is one of the largest sectors of the industry. Most of the tasks associated with this sector are carried out at worksites that are defined by their dynamism, decentralization, temporality, and the intervention of a large number of workers, subcontractors, machinery, equipment, and materials. These characteristics make this sector a great challenge for the implementation of ICTs. In this paper, the benefits of the use of the Fifth-Generation (5G) of mobile networks in the construction industry are presented. To that end, first, the digitization and automation needs of the sector are jointly analyzed, establishing different use cases and identifying the requirements of each one. Second, the main characteristics of 5G that address these use cases are identified. Third, a global framework for the application of 5G technology to the construction industry is proposed. Finally, an overview of some directions for future work are provided.

4.2 Anomaly Detection and Analysis Framework for Mobile Networks

J. Mendoza, I. de-la-Bandera, J. Burgueño, C. Morillas, D. Palacios, and R. Barco, "Anomaly Detection and Analysis Framework for Mobile Networks," in *2021 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit)*, Porto (Portugal), Jun. 2021. DOI: 10.1109/EuCNC/6GSummit51104.2021.9482529.

Abstract: Proper management of failures in mobile communication networks is essential to provide quality services to users. This management consists of several tasks, being the first of them the detection of network failures. To carry out this task, key performance indicators (KPIs) that reflect the network state are analyzed. However, due to the different nature of these KPIs, the same detection method is not able to correctly find the anomalies in all of them. In addition, most of the techniques proposed at the moment, focus on the detection of certain types of anomalies. This paper proposes a framework for the detection of anomalies, capable of finding different types of anomalies in KPIs of different nature. This framework includes as well certain configuration parameters that allow to perform the detection based on the policies of network operators. As a result, the proposed framework indicates which of the anomalies found are actually KPI degradations as well as the start and end time of each degradation, and its percentage of degradation with respect to the normal behavior of the KPI.

Chapter 5

Development and Evaluation tools

5.1 Forecasting Framework for Mobile Networks based on Automatic Feature Selection

J. Mendoza, I. de-la-Bandera, D. Palacios, and R. Barco, "Forecasting Framework for Mobile Networks based on Automatic Feature Selection," *IEEE Transactions on Network and Service Management*, Under review, 2022.

Abstract: Traditionally, mobile network management has been based on reactive systems, where corrective actions are taken when a failure or a suboptimal network performance is detected. However, the requirements of low latency and high throughput associated with 5G new services, make these reactive systems insufficient to manage the new needs of users. Thus, the focus of mobile network management has changed to a proactive approach, where preventive actions are taken to avoid failures and suboptimal network performance. Moreover, in 5G, management algorithms are expected to make use of large amounts of information sources. The use of this large amount of information and the need to use historical data to generate forecasting models, may cause a loss of accuracy. To address these challenges, a forecasting framework is proposed in this work. The framework is based on the use of automatic feature selection techniques in both spatial and temporal dimensions as a pre-prediction stage. In this way, the proposed framework can improve the accuracy of other prediction schemes when using large amounts of data as input. The proposed scheme has been tested using different forecasting techniques. In addition, the impact of the proposed framework on predictions of different future lags has been analyzed.

5.2 Modeling the UE-perceived Cellular Network Performance following a Controller-based Approach

J. Mendoza, D. Palacios, I. de-la-Bandera, E. Baena, E.J. Khatib, and R. Barco, ”Modeling the UE-perceived Cellular Network Performance following a Controller-based Approach,” *EURASIP Journal on Wireless Communications and Networking*, vol. 2019, no. 1, pp. 1–12, Dec. 2019. DOI: 10.1186/s13638-019-1596-9.

Abstract: During the last few years, mobile communication networks have experienced a huge evolution. This evolution culminates with the arrival of the fifth generation (5G) of mobile communication networks. As a result, the complexity of network management tasks has been increasing and the need to use automatic management algorithms has been demonstrated. However, many mobile network operators (MNOs) are reluctant to evaluate these algorithms in their networks. To address this issue, in this paper, a modeling approach is proposed. In this sense, the behavior of a commercial network, as it is perceived by user equipments (UEs), has been replicated in a research testbed using a three-step modeling process. The first step consists on performing a measurement campaign in several external networks. The second step is composed of the measurement campaign result analysis and the classification of the results in different types of scenarios. Finally, the third step is related to the application of a modeling algorithm in a research testbed. In order to perform the last step, the use of a method based on a controller is proposed. The modeling process presented in this paper allows to replicate the network behavior from users located in different areas and with different conditions point of view. Moreover, the use of a testbed environment can help to avoid downtime in commercial networks caused by possible algorithm bugs.

Chapter 6

Optimization

6.1 On the Capability of QoE Improvement based on the Adjustment of RLC Parameters

J. Mendoza, I. de-la-Bandera, D. Palacios, A. Herrera-Garía, and R. Barco, "On the Capability of QoE Improvement based on the Adjustment of RLC Parameters," *Sensors*, vol. 20, no. 9, p. 2474, Apr. 2020. DOI: 10.3390/s20092474.

Abstract: The constant evolution in mobile communications networks have led operators to seek new techniques to optimize their mobile networks with the objective of satisfying the expectations of the users. In this way, traditional optimization techniques based on improving radio indicators, have given way to new techniques based on improving the quality of experience (QoE) perceived by users. This paper is focused on analyzing the impact of the adjustment of radio link control (RLC) layer configuration parameters on the QoE perceived by the users of two different types of services. Firstly, an evaluation of the QoE experienced by the user of a real-time video streaming service with respect to the transmission buffer size of the RLC layer in unacknowledged mode (UM) has been carried out. Secondly, the QoE perceived by the user of a file transfer service in relation to the variation of the configuration parameters of the RLC layer in acknowledged mode (AM) has been evaluated. The study, which has been carried out in a simulated cellular environment, has been performed for different system bandwidth values, thus proving the relationship between the QoE perceived by the users, the optimal RLC configuration parameters values and the available bandwidth.

6.2 QoE Optimization in a Live Cellular Network through RLC Parameter Tuning

J. Mendoza, I. de-la-Bandera, D. Palacios, and R. Barco, "QoE Optimization in a Live Cellular Network through RLC Parameter Tuning," *Sensors*, vol. 21, no. 16, p. 5619, Aug. 2021. DOI: 10.3390/s21165619.

Abstract: The mobile communication networks sector has experienced a great evolution during the last few years. The emergence of new services as well as the growth in the number of subscribers have motivated the search for new ways to optimize mobile networks. In this way, the objective pursued by optimization techniques has been evolving, shifting from the traditional optimization of radio parameters to the improvement of the quality perceived by users, known as quality of experience (QoE). In mobile networks, the radio link control (RLC) layer provides a reliable link between both ends of the communication and has a great impact on the QoE. In this paper, the optimization of the QoE for users based on the adjustment of the RLC layer is proposed. For this purpose, two typical services demanded by the users of mobile networks have been selected: the real-time video streaming service and file transfer service. For a broader view of the behavior of the QoE in relation to RLC, optimization tests have been carried out in scenarios with different system bandwidths. In this way, the relationship between the QoE and the optimal configuration of RLC in different network load situations has been analyzed. A proof of concept has been carried out to show the capability of this optimization. To that end, both a cellular network simulator and a live cellular network devised for research purposes have been used.

6.3 Proactive Dual Connectivity for Automated Guided Vehicles in Outdoor Industrial Environment

J. Mendoza, I.Z. Kovács, M. López, T.B. Sørensen, R.O. Adeogun, I. de-la-Bandera, and R. Barco, "Proactive Dual Connectivity for Automated Guided Vehicles in Outdoor Industrial Environment," *IEEE Access*, vol. 10, pp. 54149–54163, May 2022. DOI: 10.1109/ACCESS.2022.3176730.

Abstract: 5G communication systems are one of the major enabling technologies to meet the needs of Industry 4.0. This paper focuses on the use case of automated guided vehicles (AGVs) in an outdoor industrial scenario. To meet the communication requirements in these type of use cases, dual connectivity (DC) with resource aggregation in the uplink (UL) is generally proposed. However, uncontrolled use of DC schemes may negatively affect the network causing effects such as reduced network capacity, increased signaling, and increased interference. To overcome these issues, this paper proposes and evaluates the use of a proactive DC activation algorithm based on the instantaneous quality of service (QoS) and network conditions. The proposed algorithm has two phases, a first phase in which the QoS prediction is performed, and a second phase in which the DC activation decision is made. The performance evaluation of the algorithm has been carried out in two different scenarios: a single-frequency (SF) network and a dual-frequency (DF) network; and compared to two baselines. Our results show that our predictive DC algorithm is sufficiently robust and can offer benefits in terms of reduced signaling and increased UL performance, especially in scenarios with low to medium traffic load.

Chapter 7

Conclusions

This chapter presents a summary of the research conducted during this thesis. For this purpose, this chapter is divided into three sections. Section 7.1 provides a review of the objectives pursued in this thesis, highlighting the main contributions of each of them. Section 7.2 suggests some lines of future work related to the research carried out. Finally, Section 7.3 shows a list of publications as well as other activities related to this thesis.

7.1 Contributions

This thesis aims at developing automatic control techniques to improve the performance of mobile networks. To that end, challenges in different phases of the optimization process have been identified and required objectives to solve these problems have been defined. A total of eight objectives have been established, which are distributed among the studied phases of the optimization process as follows. Obj. 1 and 2 are related to the study tasks prior to the development of optimization algorithms. These tasks are intended to obtain a deeper understanding of the networks and their environments. Obj. 3 and 4 aim to provide tools to improve the performance of optimization algorithms. Finally, Obj. 5, 6, 7, and 8 refer to the development of optimization algorithms. The contributions related to each of these objectives are presented below:

Obj. 1: To study the feasibility of using 5G to conduct the digitization of the construction sector.

- In relation to this objective, a study has been carried out on the benefits that 5G technology provides to enable the digitization of the construction sector. To this end, first, the use cases related to the digitization and automation of the construction sector are identified. For each of these use cases, their needs in terms of communication and connectivity as well as the challenges they pose for communication technologies are established. To the authors' knowledge, this is the first time that communication needs for the digitization of the construction sector have been jointly analyzed.

- Secondly, 5G technology is presented, describing its main features and functionalities that will allow to solve the challenges identified in the construction use cases and meet their needs. These characteristics refer, on the one hand, to the 5G service categories: eMBB, URLLC and mMTC; and, on the other hand, to some of the main new functionalities that are implemented in these networks and that will allow covering the requirements of the different service categories: network slicing, MC, massive MIMO and vehicular communications. In addition, it also provides an insight into the role that the integration of 5G technology and satellite communications will play in the digitization of the construction sector.
- Next, a high-level architecture is proposed for the implementation of building digitization through the integration of 5G technology. The proposed architecture not only considers tasks related to the construction sector, but also takes into account those tasks related to the management of the 5G network that will allow to provide a suitable and optimized services.
- Finally, some of the main line of future work are presented. These lines cover both the need for the development of applications in the field of construction that allow its automation and digitization as well as those problems that may arise from the use of 5G technology in this sector.

Obj. 2: To propose a system for detecting different types of anomalies in KPIs of different nature.

- To meet this objective, an anomaly detection system has been designed. Unlike others previously proposed in the state of the art, the designed system is capable of detecting isolated and long-lasting anomalies in both periodic and non-periodic KPIs. The system takes as input time series with historical data of KPIs, performing anomaly detection for each KPI independently. As output, the proposed system provides the start and end time of each of the detected anomalies, as well as their severity in terms of percentage of degradation with respect to the KPI behavior under normal circumstances. Thus, the system offers a complete analysis of anomalies and degradations found in a wide variety of KPIs, being very useful to perform tasks such as data labeling, or for in-depth studies of anomalies.

- The performance of the anomaly detection system has been evaluated using a dataset of a real LTE-A network. The results show that the system is able to detect with high accuracy the degradations that occur in the different KPIs.

Obj. 3: To propose a framework based on an efficient information processing to improve prediction accuracy.

- A prediction framework based on the use of automatic feature selection techniques has been developed. This framework aims to improve the accuracy of KPI predictions made in the field of mobile communications, giving impetus to the further development of proactive network management algorithms. For this purpose, a two-dimensional feature selection is proposed, in which not only the most relevant KPIs are selected to predict another target KPI, but also the most relevant time instants of each KPI. This feature selection is performed prior to the prediction. In this way, the proposed system improves the prediction accuracy and reduces the complexity of the predictive models obtained.
- To validate the performance of the proposed framework, batteries of tests have been performed using prediction algorithms of different complexity (LR, SVR and GRU) in the prediction phase of the framework. In addition, the impact of using the proposed framework to predict different time instants in the future has been analyzed.
- The performance of the algorithm has been compared with other solutions proposed in the state of the art, thus demonstrating that the proposed framework is able to achieve better results.

Obj. 4: To propose a mechanism for modeling test environments.

- Following this objective, in this thesis a method that allows the modeling of test environments in such a way that they mimic the behavior of real networks or areas of these from the UE's point of view has been designed. In this way, it is intended to obtain a test environment with the necessary configuration to perform proofs of concept of network management algorithms in an environment with a behavior as close as possible to a real network. To the authors' knowledge, in the literature, there are no other works related to the modeling of testbeds.

- Modeling the network from the UE's perspective provides an E2E view of network behavior. For that end, metrics such as RSRP and throughput has been used. Thus, the objective of the proposed method is to get the UEs connected to the testbed to obtain similar RSRP and throughput values to those of the UEs connected to the real network to be imitated. For this purpose, the proposed method performs an automatic adjustment of different configuration parameters of the testbed.
- To evaluate the modeling method, tests have been carried out on the UMA-HetNet network, using as input the results of a measurement campaign carried out on the networks of some of the main European operators within the framework of the MONROE project.

Obj. 5: To study the impact of RLC configuration parameters adjustment on the QoE.

- An analysis on the impact of adjusting the configuration parameters of the RLC layer on users' QoE has been performed. In this analysis, a more detailed study than in those found in the state of the art is performed. It evaluates the two operating modes of the RLC layer: AM and UM. To this end, two of the most used services in a mobile network are used: file transfer and video streaming. Each of these services use a different RLC operation mode. In addition, more configuration parameters are studied than in previous works, thus allowing to obtain a better understanding of the functioning of this layer. Another contribution related to this work is the analysis of the effect of RLC configurations on QoE.
- The study has been performed in a simulated LTE environment. As a result of this study, a series of recommendations for the configuration of the RLC layer in LTE are obtained. Due to the similarities between the RLC layers of LTE and 5G technologies, this analysis could be reproduced in 5G networks, thus obtaining recommendations for the configuration of the RLC layer in this technology.

- Finally, this study demonstrates the possibility of improving the QoE through the configuration of the RLC layer, thus opening the way to the development of algorithms for automatically adjusting the configuration of this layer.

Obj. 6: To propose an algorithm for QoE improvement based on the adjustment of RLC configuration parameters.

- The RLC layer is responsible for providing a reliable link for data transmission, thus having a large impact on the QoE perceived by users. Despite this, QoE optimization based on RLC layer tuning has not been addressed in the state of the art. In this thesis, an algorithm to maximize the QoE perceived by users through the adjustment of the RLC layer configuration parameters has been developed. This algorithm aims to automatically configure the RLC layer to provide the best possible QoE to users of different types of services. Thus, this work extends the study carried out in response to Obj. 5.
- The algorithm evaluation tests have been performed both in a simulated LTE environment and in a real test network. The tests performed cover the optimization of two different services: file transfer and video streaming. Furthermore, these tests have been performed under different conditions of available bandwidth in the network. The tests show that the proposed algorithm is able to converge to the maximum QoE values in each situation, there being a dependency between the values of the RLC layer configuration parameters and the network conditions.

Obj. 7: To propose a MC activation algorithm for the AGVs use case in an industrial environment.

- An algorithm to automatically and dynamically activate DC for the AGVs use case in an outdoor industrial environment has been design. This algorithm relies on QoS and the RSRP difference between the primary and secondary cells to make decisions about when to activate or deactivate DC. The decisions are made independently for each AGV.
- For proper operation, AGVs transmit video images in real time to their central guidance control system, from which they receive control commands. Thus, in this use case, the uplink is much more loaded than the downlink. For this reason, and unlike most of the work in the literature, this algorithm

focuses on uplink DC management. Specifically, the proposed DC scheme is the combination of two carriers in a single channel aggregated from an AGV to two nodes in the network.

Obj. 8: To propose a proactive optimization algorithm to avoid performance degradations in the AGVs use case in an industrial environment.

- Due to the criticality of AGV communications with its central guidance control system, it is deemed necessary to carry out a proactive management that allows early action in the event of possible performance degradation. Thus, a prediction stage has been added to the previous algorithm, resulting in a single algorithm in which DC activation is performed proactively. Thus, DC activation or deactivation decisions are based on the predicted QoS. To predict the QoS, a simple scheme based on the use of a clustering algorithm and logistic regression is proposed, thus facilitating the integration of the algorithm in real network management tools.

- The evaluation of the algorithm has been carried out in a simulated environment. Specifically, a simulator has been implemented based on a real industrial scenario in which AGVs are currently used to perform certain tasks. In the current scenario the number of AGVs is limited, they move at low speed and are equipped with LTE technology, using a public network. Thus, it is proposed the implementation of a private 5G network, which will allow to increase the number of AGVs connected to the network and the speed at which they move through the scenario.

- The proposed algorithm has been evaluated at two levels: QoS prediction accuracy evaluation and radio performance evaluation in terms of QoS gain. In addition, the performance of the algorithm has been compared with two baselines. The results show that the benefits of the proposed algorithm in terms of uplink performance improvement and signaling reduction are especially relevant in medium-low load scenarios. Thus, it is demonstrated that the proposed algorithm is more robust than the baselines (whose performance relies on QoS autocorrelation) to changes in the radio environment and interference conditions.

7.2 Future work

Possible lines of research that might continue the work in this thesis are the following:

- Regarding the use of 5G to drive the digitization of the construction sector, this thesis has conducted a study that aims to serve as a guide for the development of specific algorithms and systems that will address the different use cases identified, thus providing concrete solutions that meet the needs of this sector. One of the main lines to be addressed in this context would be the development of a dynamic network slicing management algorithm that automatically distribute the resources among all the slices depending on the requirements of the services hosted in each slice.

- The anomaly detection performed in this thesis covers the challenges identified in terms of identifying different types of anomalies in KPIs of different nature. This detection is performed offline allowing the study of the network behavior by engineers and network experts. This work could be continued by proposing a detection system that allows to perform this anomaly detection in a proactive way, thus performing an early detection of possible failures and allowing to take decisions to avoid the occurrence of these failures. The use of this type of proactive anomaly detection systems is considered especially important in those use cases related to critical communications. On the other hand, anomaly detection could be enhanced by the use of new input parameters, such as alarms, network configuration parameters or context information to take into account environmental conditions.

- In this thesis, the use of dimensionality reduction techniques has been proposed to address the problem of increasing the number of information sources and thus the amount of data in 5G networks. Although these techniques contributes to deal with this problem, they alone will not be sufficient in environments with huge amounts of data. In this sense, the use of big data techniques for data processing becomes indispensable. Thus, a possible line of future work related to this thesis is the integration of big data techniques in the forecasting framework presented in this thesis.

- The test environment modeling mechanism proposed in this thesis could be expanded to design a more complex model that would allow taking into account a larger number of performance indicators reported by the UE as well as a larger number of network configuration parameters.

- Regarding the optimization of QoE based on the use of RLC, different lines of future work could be pursued. On the one hand, tests could be carried out covering a larger number of configuration parameters of the RLC layer as well as using other services such as web browsing, which are becoming indispensable in the daily life of mobile network users. On the other hand, the controller used to perform this optimization could be replaced by ML algorithms that allow a dynamic adaptation of the RLC layer to changes in the scenario.

- Finally, regarding MC management, this thesis has proposed a system with the objective of improving communication throughput. This is achieved by aggregating the radio links that connect the user to the network. However, other MC schemes could be used to improve reliability by transmitting duplicated information through the different links that connect the user to the network. Thus, as a line of future work, the reuse of the proactive DC activation scheme presented in this thesis could be used to meet the objectives of other use cases in the framework of the new scenarios covered by 5G networks.

7.3 Publications and projects

The following subsections present the publications and activities related to this thesis.

7.3.1 Journals

Publication arising from this thesis

[I] J. Mendoza, I. de-la-Bandera, C.S. Álvarez-Merino, E.J. Khatib, J. Alonso, S. Casalderrey-Díaz, and R. Barco, "5G for Construction: Use Cases and Solutions," *Electronics*, vol. 10, no. 14, p. 1713, Jul. 2021.

[II] J. Mendoza, I. de-la-Bandera, D. Palacios, and R. Barco, "Forecasting Framework for Mobile Networks based on Automatic Feature Selection," *IEEE Transactions on Network and Service Management*, Under review, 2022.

[III] J. Mendoza, D. Palacios, I. de-la-Bandera, E. Baena, E.J. Khatib, and R. Barco, "Modeling the UE-perceived Cellular Network Performance following a Controller-

based Approach," *EURASIP Journal on Wireless Communications and Networking*, vol. 2019, no. 1, pp. 1–12, Dec. 2019.

[IV] J. Mendoza, I. de-la-Bandera, D. Palacios, A. Herrera-Garía, and R. Barco, "On the Capability of QoE Improvement based on the Adjustment of RLC Parameters," *Sensors*, vol. 20, no. 9, p. 2474, Apr. 2020.

[V] J. Mendoza, I. de-la-Bandera, D. Palacios, and R. Barco, "QoE Optimization in a Live Cellular Network through RLC Parameter Tuning," *Sensors*, vol. 21, no. 16, p. 5619, Aug. 2021.

[VI] J. Mendoza, I.Z. Kovács, M. López, T.B. Sørensen, R.O. Adeogun, I. de-la-Bandera, and R. Barco, "Proactive Dual Connectivity for Automated Guided Vehicles in Outdoor Industrial Environment," *IEEE Access*, vol. 10, pp. 54149–54163, May 2022.

Publication related to this thesis

[VII] I. de-la-Bandera, D. Palacios, J. Mendoza, and R. Barco, "Feature Extraction for Dimensionality Reduction in Cellular Networks Performance Analysis," *Sensors*, vol. 20, no. 23, p. 6944, Dec. 2020.

[VIII] J. Burgueño, I. de-la-Bandera, J. Mendoza, D. Palacios, C. Morillas, and R. Barco, "Online Anomaly Detection System for Mobile Networks," *Sensors*, vol. 20, no. 24, p. 7232, Dec. 2020.

[IX] C. Rosa-Jiménez, et al., "Smart Solar Micro-exchangers for Sustainable Mobility of University Camps," *IOP Conference Series: Materials Science and Engineering*, vol. 960, no. 4, p. 042011, Dec. 2020.

[X] A. Herrera-García, 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*, vol. 14, no. 4, pp. 76–84, Dec. 2019.

7.3.2 Conferences and Workshops

Conferences arising from this thesis

[XI] J. Mendoza, I. de-la-Bandera, J. Burgueño, C. Morillas, D. Palacios, and R. Barco, "Anomaly Detection and Analysis Framework for Mobile Networks," in *2021 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit)*, Porto (Portugal), Jun. 2021.

[XII] J. Mendoza, D. Palacios, I. de-la-Bandera, and R. Barco, "Selección Automática de Características para una Gestión Proactiva Eficiente de Redes 5G," in *XXXIV Simposium Nacional de la Unión Científica Internacional de Radio (URSI 2019)*, Sevilla (Spain), Sep. 2019.

Conferences related to this thesis

[XIII] A. Herrera-García, S. Fortes, E. Baena, J. Mendoza, and R. Barco, "Modelado de Indicadores de Calidad de Servicio para la Gestión de red Extremo a Extremo," in *XXXIV Simposium Nacional de la Unión Científica Internacional de Radio (URSI 2019)*, Sevilla (Spain) Sep. 2019.

7.3.3 Related projects

This thesis was funded by the Ministry of Science, Innovation, and Universities under grant agreement FPU18/04786.

This thesis has also contributed to the following projects:

- International projects:
  - MONROE: Measuring Mobile Broadband Networks in Europe, funded under: H2020-ICT-11-2014, project number: 644399.
  - ONE5G: E2E-aware Optimizations and advancements for the Network Edge of 5G New Radio, funded under H2020-ICT-2016-2, project number: 760809.
- National projects:
  - NEREA: Network Strategy And Evolution Advisor, funded by Spanish Ministry of Economy and Competitiveness and ERDF, project number: RTC-

2017-6661-7.

– PENTA: Provisión de servicios PPDR a través de Nuevas Tecnologías de Acceso radio, funded by Junta de Andalucía and ERDF, project number: PY18-4647.

– DAMA5G: Detección de Anomalías Multivariable Asistida, funded by Junta de Andalucía and ERDF, project number: UMA-CEIATECH-11.

– TEDES5G: Técnicas 5G para una Edificación Eficiente y Segura, funded by Junta de Andalucía and ERDF, project number: UMACEIATECH-12

– MUSE: Massive USer Experience Assessment and Prediction for Mobile Networks, funded by Junta de Andalucía and ERDF, project number: UMA-CEIATECH-13.

– Métodos de planificación y optimización de la calidad de experiencia en redes B4G, funded by the Spanish Ministry of Economy and Competitiveness, project number: TEC2015-69982-R.

– Gestión integral avanzada de funciones SON para redes móviles futuras, Proyectos de Execelencia, Junta de Andalucía, project number: P12-TIC-2905.

– MICROSOL: Microintercambiadores solares inteligentes: Prototipo de arquitecturas del sol para la movilidad sostenible de la UMA, funded by I Smart-Campus Plan of University of Málaga.

7.3.4 Research stay

This thesis involved a six month stay in Aalborg (Denmark), collaborating with Aalborg University and Nokia-Bell Labs Aalborg in proactive DC management in an industrial environment. The stay took place between September 2020 and February 2021 and was supervised by István Z. Kovács and Troels B. Sørensen.

Appendix A

Summary (Spanish)

A.1 Introducción

A.1.1 Antecedentes y justificación

Desde sus inicios, las comunicaciones móviles no han dejado de evolucionar, ofreciendo cada vez más servicios y de mejor calidad a sus usuarios. Lejos han quedado los tiempos en los que las comunicaciones móviles sólo servían para hacer llamadas telefónicas y enviar mensajes de texto. Hoy en día, los teléfonos móviles forman parte de nuestra vida cotidiana, proporcionándonos acceso a Internet y a miles de aplicaciones como la mensajería instantánea, las redes sociales, o la banca y las compras en línea. La expansión de los servicios de comunicaciones móviles se ha extendido más allá de las comunicaciones entre personas para incluir las comunicaciones entre personas y máquinas, como las aplicaciones de control remoto, o entre máquinas, como las comunicaciones vehiculares. Así, las comunicaciones móviles se han convertido en un elemento clave para impulsar la transformación digital de la sociedad y la economía.

En este contexto, las tecnologías móviles de quinta generación (*Fifth Generation*, 5G) surgen no sólo con el objetivo de proporcionar servicios mejorados de banda ancha móvil (*enhanced mobile broadband*, eMBB) respecto a las generaciones anteriores, sino también de cubrir nuevos casos de uso relacionados con las comunicaciones críticas, conocidas como comunicaciones ultra fiables de baja latencia (*ultra-reliable low-latency communications*, URLLC), y con el uso masivo de dispositivos tipo máquina como, por ejemplo, el Internet de las Cosas (*Internet of Things*, IoT), estos servicios se conocen como comunicaciones masivas de tipo máquina (*massive machine-type communications*, mMTC) [1, 2]. De este modo, el 5G pretende abarcar una gran variedad de servicios, convirtiéndose en una tecnología habilitadora para llevar a cabo la digitalización y automatización de diferentes sectores industriales, como la agricultura, la energía, la manufactura, la sanidad o la automoción [3].

La imparable evolución de las comunicaciones móviles hace que sus tareas de gestión y operación sean cada vez más complejas. Para garantizar unos gastos de capital (*capital expenditures*, CAPEX) y unos gastos operativos (*operational expenditures*, OPEX) mínimos y, al mismo tiempo, satisfacer la demanda de los consumidores y ofrecer servicios de alta calidad, los operadores de redes móviles (*mobile network operators*, MNO) centran sus esfuerzos en la automatización de estas tareas, lo que da lugar a lo que se conoce como redes autoorganizadas (*self-organizing networks*, SON) [4].

Los principios de las SON fueron establecidos por primera vez por la *Next-Generation Mobile Network* (NGMN) en 2008 [5,6]. Posteriormente, el *Third Generation Partnership Project* (3GPP) incluyó los requisitos de las SON en sus estándares [7], agrupando las funcionalidades de las SON en tres categorías: autoconfiguración [8], autooptimización [8] y autocuración [9]. Por un lado, la autoconfiguración abarca todas aquellas tareas relacionadas con la configuración automática de los elementos de red que hayan sido recientemente desplegados. Por otro lado, la autooptimización incluye aquellas funciones relacionadas con el reajuste de los parámetros de configuración de la red, de manera que esta sea capaz de adaptarse dinámicamente a los cambios del entorno (por ejemplo, al clima, a los patrones de tráfico o a las interferencias) y proporcionar servicios de calidad en cualquier momento. Por último, la autocuración engloba aquellas tareas encaminadas a detectar posibles fallos en la red, diagnosticar la causa raíz de los mismos y determinar acciones de compensación y recuperación necesarias. Esta tesis se centra en las tareas de autooptimización.

Dada la importancia de las técnicas de SON, en los últimos años, múltiples proyectos internacionales de gran impacto se han centrado en la investigación y el desarrollo de estas técnicas en redes *Long-Term Evolution* (LTE) y 5G. Entre estos proyectos se encuentran los siguientes: SEMAFOUR [10], SELFNET [11], ONE5G [12], SONNET [13], IMMINENCE [14] y LOCUS [15]. A pesar de los grandes avances de estos proyectos, el hecho de que las redes de comunicaciones móviles estén en constante evolución, hace que los algoritmos de SON también deban evolucionar para adaptarse a los nuevos servicios, casos de uso y requisitos de las redes.

Tradicionalmente, la optimización de las redes móviles se ha centrado en el análisis y la mejora de los indicadores clave de calidad (*key performance indicators*, KPI) de la red de acceso radio (*radio access network*, RAN), como la tasa de bloqueo o la tasa de llamadas caídas [16]. Sin embargo, en los últimos años, debido a la expansión de las comunicaciones móviles y a las demandas cada vez más exigentes de los usuarios, el enfoque en términos de optimización de la red se ha ido acercando gradualmente al usuario. Así, trabajos como [17] se centran en la optimización de los indicadores clave de calidad (*key quality indicators*, KQI) que proporcionan información a nivel de aplicación sobre la calidad de los servicios ofrecidos a los usuarios. Actualmente, los expertos en gestión de redes centran su atención en la optimización de la calidad de experiencia (*quality of experience*, QoE) [18, 19]. Esta métrica permite realizar una gestión centrada en el usuario con una visión global de extremo a extremo (*end-to-end*, E2E) de la red.

A medida que las redes crecen, también lo hace el número de fuentes de información y la cantidad de datos que recogen. Toda esta información es útil para el desarrollo de algoritmos de SON que controlen diferentes aspectos de la red. Para diseñar un algoritmo específico, la correcta selección de la información a utilizar es de vital importancia. El uso de información no relevante conduce no sólo al desarrollo de algoritmos y modelos más complejos, al tener un mayor número de parámetros de entrada, sino también a una pérdida de eficiencia y eficacia de estos algoritmos, que serán menos precisos y/o exactos en sus resultados. Tradicionalmente, la selección de esta información se ha realizado de forma manual [20–24]. Estas técnicas manuales se caracterizan por requerir mucho tiempo. Por este motivo, los expertos en gestión de redes suelen utilizar los mismos KPI como entrada a los algoritmos de gestión, lo que puede no dar siempre los mejores resultados. Para resolver este problema, es necesario utilizar técnicas de reducción de la dimensionalidad. Estas técnicas tienen como objetivo seleccionar o extraer las características más relevantes para resolver un determinado problema.

La aparición de nuevos servicios en 5G con requisitos cada vez más exigentes en cuanto a baja latencia y alta velocidad de datos hace que los algoritmos tradicionales de SON basados en métodos reactivos que ejecutan una acción cuando se detecta un fallo o una degradación del rendimiento en la red, no sean suficientes [25–27]. Así, trabajos recientes se centran en métodos proactivos de gestión de la red, capaces de anticiparse a posibles eventos. En este contexto, múltiples autores han centrado su atención en la implementación de mecanismos de predicción para estimar el valor futuro de diferentes aspectos de la red como la carga de celdas [28], la calidad del canal radio [29], la localización de los usuarios [30], el tráfico cursado en la red [31–37], la QoE [38, 39], la demanda de servicios [40] o las métricas de la RAN [41]. Además de estos mecanismos de predicción, en la literatura también existen trabajos que proponen métodos proactivos para realizar tareas de autooptimización, como la gestión dinámica de antenas [42] y haces [43], el balanceo de carga [44], el ahorro de energía [45], la configuración de la cloud-RAN [46, 47], la asignación de recursos [48, 49], o la gestión de handover (HO) [50, 51]; y tareas de autocuración, como la detección de fallos en la red [52, 53]. A pesar de la extensa literatura asociada a este tema, la gestión proactiva de la red sigue considerándose un tema candente en la actualidad, donde el objetivo es conseguir algoritmos de predicción más precisos, con resultados más fiables para la toma de decisiones. Además, se considera necesario el desarrollo de algoritmos proactivos para la gestión de las nuevas funcionalidades del 5G, como la multiconectividad (*multi connectivity*, MC) o el *network slicing*.

A.1.2 Objetivos

El objetivo principal de esta tesis es mejorar el rendimiento de la red utilizando técnicas de control automático. Para ello, en esta tesis se abordan diferentes pasos del proceso de optimización. En primer lugar, se realizan tareas relacionadas con el estudio de las características y los requisitos de las redes y su entorno. En segundo lugar, se desarrollan mecanismos para mejorar el rendimiento y la evaluación de los algoritmos de optimización. Finalmente, se desarrollan algoritmos de autooptimización con los siguientes propósitos: mejorar la QoE del usuario y mejorar el servicio ofrecido en los nuevos escenarios 5G mediante el uso de MC. Específicamente, las líneas de investigación abordadas en en esta tesis se pueden resumir en los siguientes objetivos (ver Fig. 1.1):

Obj. 1: Estudiar la viabilidad del uso del 5G para llevar a cabo la digitalización del sector de la construcción. Este estudio debe identificar los principales casos de uso relacionados con la digitalización del sector de la construcción. Además, debe incluir las principales funcionalidades del 5G que satisfagan las necesidades del sector. De este modo, este estudio pretende sentar las bases para la digitalización del sector de la construcción mediante el uso de la tecnología 5G.

Obj. 2: Proponer un sistema de detección de distintos tipos de anomalías en KPI de distinta naturaleza. El sistema debe ser capaz de detectar conjuntamente los diferentes tipos de anomalías que se producen en una red móvil mediante el análisis de los KPI. Como resultado, se obtendrá información de gran valor que permitirá analizar en profundidad el rendimiento de la red, aportando conocimientos para el desarrollo de algoritmos de optimización.

Obj. 3: Proponer un mecanismo basado en un procesamiento eficiente de la información para mejorar la precisión de la predicción. Este mecanismo hará uso de técnicas de reducción de la dimensionalidad como paso previo a la predicción de KPI. Así, el mecanismo simplificará los modelos de predicción y eliminará el ruido introducido en ellos por el uso de características no relevantes. Como resultado, este mecanismo aumentará la precisión de los algoritmos de predicción propuestos en el estado del arte.

Obj. 4: Proponer un mecanismo de modelado de redes de prueba. El mecanismo tendrá como objetivo que la red de pruebas se comporte de la misma manera que una red real o una zona de la misma desde el punto de vista del (*user equipment*, UE). Así, este algoritmo permitirá configurar un entorno de pruebas en el que se pueda realizar la evaluación de diferentes algoritmos de gestión de red.

Obj. 5: Estudiar el impacto del ajuste de los parámetros de configuración de RLC en la QoE. El objetivo de este estudio es analizar el comportamiento de la capa RLC así como el impacto del reajuste de sus parámetros de configuración en la QoE percibida por los usuarios. De este modo, este estudio pretende sentar las bases para el desarrollo de futuros algoritmos de optimización basados en el ajuste de la capa RLC.

Obj. 6: Proponer un algoritmo para la mejora de la QoE basado en el ajuste de los parámetros de configuración de RLC. Este objetivo está relacionado con el Obj. 5. Se trata de diseñar y desarrollar un algoritmo que realice automáticamente ajustes en los parámetros de configuración de la capa RLC para maximizar la QoE percibida por los usuarios. Este algoritmo se desarrollará en base a los conocimientos adquiridos en el estudio realizado previamente en el Obj. 5.

Obj. 7: Proponer un algoritmo de activación de MC para el caso de uso de AGV en un entorno industrial. Este objetivo se refiere al diseño y desarrollo de un algoritmo que garantice el cumplimiento de las necesidades de comunicación de los AGV desplegados en un entorno industrial 4.0. Así, el algoritmo propuesto debe ser capaz de controlar de forma dinámica y automática la activación de la MC para aquellos AGVs que lo requieran.

Obj. 8: Proponer un algoritmo de optimización proactiva para evitar degradaciones de rendimiento en el caso de uso de AGV en un entorno industrial. Este algoritmo debe ser capaz de prever futuras degradaciones en el rendimiento de la red y proponer de manera anticipada la ejecución de acciones para evitar que estas degradaciones se produzcan.

A.2 Descripción de los resultados

En esta sección se presentan los resultados derivados de esta tesis. Estos trabajos responden a los retos y objetivos establecidos en la Sección 1.2. La Figura 3.1 muestra la relación entre los retos, los objetivos y los resultados a los que responden. En la figura, cada trabajo se representa como un bloque individual, indicando en qué capítulo de esta tesis se incluye. En las siguientes subsecciones se ofrece un resumen de cada uno de los trabajos que sustentan esta tesis.

A.2.1 5G para la construcción: Casos de uso y soluciones [I] (Capítulo 4.1)

El primer trabajo derivado de esta tesis se incluye en el Capítulo 4, que abarca todas aquellas tareas relacionadas con el estudio de las características y requisitos de las redes y sus entornos. En concreto, este trabajo expone los beneficios que el uso de la tecnología 5G podría aportar al sector de la construcción (Obj. 1). A pesar de ser uno de los mayores sectores de la industria, el sector de la construcción es uno de los sectores en los que el impacto de la cuarta revolución industrial ha sido menor. Esto se debe a las condiciones particulares del sector, donde la mayor parte del trabajo se realiza en obras caracterizadas por su dinamismo, descentralización y temporalidad. Así, la automatización y digitalización de este sector presenta múltiples retos para la implantación de las tecnologías de la información y la comunicación (*information and communication technologies*, ICT). Este trabajo se centra en los retos asociados a la implantación de las redes de comunicación.

Para ello, en primer lugar, se definen los casos de uso asociados a la digitalización de la construcción, identificandose los principales retos de cada uno de ellos en relación con el uso de las tecnologías de comunicación. En segundo lugar, se presentan las principales características del 5G que permitirían dar respuesta a los retos anteriormente señalados. A continuación, se propone una arquitectura a alto nivel para la integración del 5G en el sector. Por último, se destacan las principales líneas de trabajo futuro identificadas por los autores.

A.2.2 Mecanismo de detección y análisis de anomalías en redes móviles [XI] (Capítulo 4.2)

En esta subsección se presenta el segundo de los trabajos realizados en relación con el Capítulo 4 de esta tesis. En concreto, este trabajo tiene como objetivo proponer un mecanismo holístico de detección de anomalías (Obj. 2). La solución propuesta puede detectar tanto anomalías aisladas o de corta duración como anomalías mantenidas en el tiempo en KPI de distinta naturaleza, realizando así la detección tanto en KPI periódicos como en no periódicos. Además, el mecanismo permite la configuración de ciertos parámetros por parte del operador o administrador de la red, teniendo así en cuenta las políticas que estos utilizan para determinar si el comportamiento de la red es aceptable o no. En este sentido, este mecanismo proporciona un análisis completo de las anomalías encontradas en una amplia variedad de KPI, siendo muy útil para realizar tareas como el etiquetado de datos o la realización de estudios detallados del rendimiento de la red con el objetivo de desarrollar algoritmos de gestión de fallos u optimización.

Para analizar y realizar la detección de forma conjunta en KPI periódicos y no periódicos, el mecanismo incorpora una fase de detección y eliminación de periodicidades para aquellos KPI periódicos. La detección de diferentes tipos de anomalías es posible gracias al uso de dos algoritmos de detección diferentes que se utilizan en paralelo. Por un lado, para la detección de anomalías de corta duración, se utiliza un algoritmo de detección basado en umbrales. Por otro lado, para la detección de anomalías de larga duración, se utiliza un algoritmo de detección basado en los puntos de cambio de la señal. Los resultados de estos dos algoritmos se combinan mediante la operación lógica OR. Finalmente, mediante un sistema de ponderación basado en la duración de las anomalías y el porcentaje de degradación de los KPI durante las mismas, se determina cuáles de las anomalías detectadas se consideran degradaciones (anomalías severas).

La evaluación del mecanismo se ha realizzado mediante el uso de datos de una red comercial LTE-A. Los resultados muestran que el mecanismo puede detectar correctamente las anomalías, alcanzando unos resultados de exactitud y precisión del 95,94% y 87,20% respectivamente.

A.2.3 Mecanismo de predicción para redes móviles basado en la selección automática de características [II] (Capítulo 5.1)

El Capítulo 5 trata de los desarrollos de mecanismos y herramientas para mejorar el rendimiento y la evaluación de los algoritmos de optimización. El primer trabajo incluido en este capítulo aborda el uso de técnicas de procesamiento de datos previas al desarrollo de algoritmos de optimización. El uso de estas técnicas ayuda a mejorar el rendimiento de los algoritmos de gestión. En concreto, el objetivo de este trabajo es proponer un mecanismo de predicción para la mejora de la precisión de las predicciones (Obj. 3), abriendo el camino para el posterior desarrollo de algoritmos de proactivos de gestión de redes. Para ello, se propone el uso de técnicas de selección automática de características como paso previo a la predicción de KPI de red. La selección automática de características propuesta en este trabajo se aplica considerando la doble dimensión de los KPI: su tipo y su dependencia temporal. Así, la solución propuesta selecciona qué indicadores y qué instantes temporales de cada indicador son los más relevantes para predecir un KPI objetivo. Las características seleccionadas se utilizan como entrada al algoritmo de predicción.

Para evaluar el mecanismo propuesto, se ha utilizado un conjunto de datos de una red comercial LTE-A. Las pruebas, se han realizado utilizando tres algoritmos de predicción con diferente complejidad: regresión lineal (*linear regression*, LR), *support vector regression* (SVR) y *gated recurrent unit* (GRU). Además, se ha analizado el impacto de utilizar el mecanismo propuesto para predecir diferentes instantes en el futuro. El rendimiento de la solución propuesta se ha comparado con dos líneas de base: el uso de la muestra actual de todos los KPI para predecir y el uso de toda la información disponible para predecir. Los resultados muestran que el mecanismo propuesto mejora la precisión de las dos líneas de base. Además, gracias al uso de la selección automática de características bidimensional es posible conseguir con técnicas de predicción simples (LR y SVR) resultados de predicción similares a los obtenidos con técnicas de predicción más complejas (GRU).

A.2.4 Modelado del rendimiento de la red celular desde el punto de vista del UE siguiendo un enfoque basado en un controlador [III] (Capítulo 5.2)

El segundo trabajo incluido en el Capítulo 5 aborda el problema de la creación de entornos de prueba en los que sea posible probar los algoritmos antes de su implementación en redes comerciales (Obj. 4). La realización de pruebas en una red real destinada a tal efecto permite detectar posibles fallos o errores en los algoritmos antes de su implementación en redes comerciales, evitando así errores en la configuración de los parámetros que puedan dar lugar a degradaciones del servicio. En concreto, este trabajo propone un mecanismo para replicar la percepción del rendimiento de las redes comerciales desde el punto de vista del usuario en una red de pruebas, es decir, conseguir que los usuarios conectados a la red de pruebas reporten los mismos valores de los indicadores de rendimiento que los usuarios conectados a la red comercial. El mecanismo propuesto permite modelar y optimizar de forma independiente distintas áreas de las redes con comportamientos diferentes.

El proceso de modelado consta de tres pasos. El primer paso es la ejecución de una campaña de medidas en redes comerciales. El segundo paso consiste en la identificación de diferentes patrones de comportamiento en las redes medidas. Para ello, se realiza una agrupación de los datos recogidos en la campaña de medidas. Esta agrupación se realiza en base a la percepción de los usuarios del comportamiento de la red. Estos grupos se toman como entrada en el tercer paso. El tercer paso consiste en ajustar los parámetros de configuración de la red de pruebas para conseguir un comportamiento determinado desde el punto de vista del equipo de usuario UE. Para ello se propone el uso de un controlador basado en el método Taguchi.

La campaña de medidas utilizada en este trabajo se ha realizado en redes comerciales de diferentes operadores europeos. La red de pruebas utilizada es una red LTE de picoceldas desplegada en la Escuela Técnica Superior de Ingeniería de Telecomunicación de la Universidad de Málaga, denominada UMAHetNet (ver Capítulo 5).

A.2.5 Capacidad de mejora de la QoE basada en el ajuste de los parámetros de RLC [IV] (Capítulo 6.1)

Una vez completadas las tareas preliminares incluidas en los Capítulos 4 y 5, se aborda el problema de la optimización de las redes móviles. Los métodos de optimización propuestos en esta tesis se presentan en el Capítulo 6. El primer trabajo incluido en el capítulo tiene como objetivo evaluar el impacto del ajuste de los parámetros de configuración de la capa RLC en la QoE percibida por los usuarios (Obj. 5). Este trabajo amplía el análisis realizado en la literatura realizando un análisis detallado de los dos modos de funcionamiento de la capa RLC: modo no reconocido (UM) y modo reconocido (AM), y el impacto del ajuste de los parámetros de configuración de estas capas en la QoE.

Para analizar el impacto del ajuste de la capa RLC en la QoE, se utilizan dos de los servicios más utilizados en una red móvil: la transmisión de vídeo en tiempo real y la transferencia de archivos. Debido a sus diferentes requisitos en términos de latencia y rendimiento, estos servicios hacen uso de diferentes modos de funcionamiento de RLC: RLC UM, en el caso del servicio de transmisión de vídeo en tiempo real, y RLC AM, en el caso del servicio de transferencia de archivos. En primer lugar, se analiza la QoE percibida por los usuarios de un servicio de transmisión de vídeo en tiempo real en relación con el tamaño del buffer de transmisión de RLC UM. El tamaño del búfer de transmisión de RLC UM tiene un impacto directo en la pérdida de paquetes y el retardo. A continuación, se analiza la QoE percibida por los usuarios de un servicio de transferencia de archivos en relación con dos de los parámetros de configuración de RLC AM, los temporizadores: t-PollRetransmit y t-StatusProhibit. Un mal ajuste de estos parámetros de configuración afecta al retardo experimentado por los paquetes. Además, estos análisis se realizan para diferentes situaciones de carga de la red.

El estudio presentado en este trabajo ha sido realizado en una red LTE simulada. Como resultado de este estudio, se proporciona un rango de valores óptimos para cada uno de los parámetros de configuración utilizados en las diferentes situaciones analizadas. Así, este trabajo sienta las bases para el desarrollo de un algoritmo de optimización de la QoE basado en el ajuste de los parámetros de configuración de la capa RLC.

A.2.6 Optimización de la QoE en una red celular real mediante el ajuste de los parámetros de RLC [V](Capítulo 6.2)

En esta subsección se presenta el segundo de los trabajos realizados en relación con el Capítulo 6. En concreto, este trabajo propone un algoritmo para optimizar la QoE de los usuarios en una red móvil (Obj. 6) mediante el ajuste de los parámetros de configuración de la capa RLC. De este modo, este trabajo amplía el trabajo presentado en [**IV**] donde se realiza un análisis del impacto del ajuste de la capa RLC en la QoE.

El algoritmo de optimización propuesto es un controlador basado en Taguchi similar al utilizado en [**III**]. La principal diferencia de los controladores utilizados en estos dos trabajos radica en el objetivo perseguido en cada uno de ellos. Mientras que en el trabajo de modelado el controlador se utiliza con el objetivo de alcanzar determinados valores de rendimiento, en este trabajo el objetivo es maximizar la QoE percibida por los usuarios. Además, a diferencia de en el trabajo de modelado de la red, en este trabajo los parámetros modificados por el controlador son los de configuración de la capa RLC. Este trabajo abarca tanto la optimización de la QoE para los usuarios de un servicio de transmisión de vídeo en tiempo real como para los usuarios de un servicio de transferencia de ficheros.

La evaluación del algoritmo se ha llevado a cabo tanto en un entorno simulado, donde se han realizado pruebas utilizando escenarios con diferentes condiciones de carga, como en una red LTE de pruebas, la UMAHetNet.

A.2.7 Gestión proactiva de la conectividad dual para vehículos de guiado automático en un entorno industrial exterior [VI] (Capítulo 6.3)

El último trabajo incluido en el Capítulo 6 se centra en un entorno de Industria 4.0. En este nuevo paradigma industrial, la tecnología 5G se presenta como una tecnología habilitadora para satisfacer las necesidades de las nuevas aplicaciones industriales. En particular, este trabajo aborda el caso de uso de los AGV en un entorno industrial exterior. Estos AGV presentan estrictos requisitos en términos de altas velocidades de datos en el enlace ascendente. Para satisfacer las necesidades de comunicación de los AGV, se propone un sistema de activación proactiva de DC (Obj. 7 y 8).

El sistema propuesto se compone de dos etapas. En la primera etapa se lleva a cabo la predicción de la QoS. Para ello, se utiliza un algoritmo de predicción basado en el uso combinado de *clustering* y regresión logística. En la segunda etapa, se lleva a cabo la toma de decisiones sobre la activación o desactivación de DC. Esta segunda etapa implementa un algoritmo basado en reglas que hace uso de la predicción de QoS realizada en la etapa anterior y de los valores de potencia recibida de la señal de referencia (*reference signal received power*, RSRP) registrados por el usuario tanto para la celda servidora como para la celda vecina más potente.

La evaluación del método propuesto se ha llevado a cabo en un entorno 5G simulado haciendo uso de dos despliegues de red diferentes: una red con celdas pequeñas en la que todas las celdas hacen uso del mismo espectro de frecuencias y una red con celdas macro y pequeñas en la que las celdas se dividen en dos capas (una capa de celdas macro y una capa de celdas pequeñas), cada una de las cuales hace uso de una parte diferente del espectro. Además, se ha comparado el rendimiento del sistema propuesto con dos líneas de base. Los resultados muestran que el sistema propuesto es capaz de mantener en valores aceptables los errores de activación de DC que provocan la sobrecarga de señalización innecesaria en la red. Además, la solución propuesta es más robusta, siendo más resistente a los cambios en el entorno radioeléctrico y a las condiciones de interferencias.

A.3 Conclusiones

A.3.1 Contribuciones

Esta tesis tiene como objetivo el desarrollo técnicas de control automático para mejorar el rendimiento de las redes móviles. Para ello, se han identificado retos en diferentes fases del proceso de optimización y se han definido los objetivos necesarios para resolver estos problemas. En total, se han establecido ocho objetivos, que se distribuyen entre las fases estudiadas del proceso de optimización de la siguiente manera. Los Obj. 1 y 2 están relacionados con las tareas de estudio y análisis previas al desarrollo de los algoritmos de optimización. Con estas tareas se pretende obtener un conocimiento más profundo de las redes y sus entornos. Los Obj. 3 y 4 pretenden proporcionar herramientas para mejorar el rendimiento de los algoritmos de optimización. Por último, los Obj. 5, 6, 7 y 8 se refieren al desarrollo de algoritmos de optimización. A continuación se presentan las contribuciones relacionadas con cada uno de estos objetivos:

Obj. 1: Estudiar la viabilidad del uso del 5G para llevar a cabo la digitalización del sector de la construcción.

- En relación con este objetivo, se ha realizado un estudio sobre los beneficios que aporta la tecnología 5G para permitir la digitalización del sector de la construcción. Para ello, en primer lugar, se identifican los casos de uso relacionados con la digitalización y automatización del sector de la construcción. Para cada uno de estos casos de uso, se establecen sus necesidades en términos de comunicación y conectividad, así como los retos que plantean para las tecnologías de comunicación. Desde el conocimiento de los autores, esta sería la primera vez que se analizan conjuntamente las necesidades de comunicación para la digitalización del sector de la construcción.
- En segundo lugar, se presenta la tecnología 5G, describiendo sus principales características y funcionalidades que permitirán resolver los retos identificados en los casos de uso de la construcción y satisfacer sus necesidades. Estas características se refieren, por un lado, a las categorías de servicio del 5G: eMBB, URLLC y mMTC; y, por otro lado, a algunas de las nuevas funcionalidades que se implementan en estas redes y que permitirán cubrir los requisitos de las diferentes categorías de servicio: network slicing, MC, *massive multi-input multiple-output* (MIMO) y comunicaciones vehiculares. Además, también se ofrece una visión del papel que la integración de la tecnología 5G y las comunicaciones por satélite jugarán en la digitalización del sector de la construcción.
- A continuación, se propone una arquitectura de alto nivel para la implementación de la digitalización de la construcción mediante la integración de la tecnología 5G. La arquitectura propuesta no sólo considera las tareas relacionadas con el sector de la construcción, sino que también tiene en cuenta aquellas tareas relacionadas con la gestión de la red 5G que permitirán proporcionar unos servicios adecuados y optimizados.
- Por último, se presentan algunas de las principales líneas de trabajo futuro. Estas líneas abarcan tanto la necesidad del desarrollo de aplicaciones en el ámbito de la construcción que permitan su automatización y digitalización como aquellos problemas que puedan surgir del uso de la tecnología 5G en este sector.

Obj. 2: Proponer un sistema de detección de distintos tipos de anomalías en

KPI de distinta naturaleza.

- Para cumplir con este objetivo, se ha diseñado un sistema de detección de anomalías. A diferencia de otros propuestos anteriormente en el estado del arte, el sistema diseñado es capaz de detectar anomalías aisladas y de larga duración tanto en KPI periódicos como no periódicos. El sistema toma como entrada series temporales con datos históricos de KPI, realizando la detección de anomalías para cada KPI de forma independiente. Como salida, el sistema propuesto proporciona la hora de inicio y fin de cada una de las anomalías detectadas, así como su gravedad en términos de porcentaje de degradación respecto al comportamiento del KPI en circunstancias normales. Así, el sistema ofrece un análisis completo de las anomalías y degradaciones encontradas en una amplia variedad de KPI, siendo muy útil para realizar tareas como el etiquetado de datos, o para la realización de estudios en profundidad de las anomalías.
- El rendimiento del sistema de detección de anomalías se ha evaluado utilizando un conjunto de datos de una red LTE-A real. Los resultados muestran que el sistema es capaz de detectar con alta precisión las degradaciones que se producen en los diferentes KPI.

Obj. 3: Proponer un mecanismo basado en un procesamiento eficiente de la información para mejorar la precisión de la predicción.

- Se ha desarrollado un mecanismo de predicción basado en el uso de técnicas de selección automática de características. Este mecanismo tiene como objetivo mejorar la precisión de las predicciones de KPI realizadas en el ámbito de las comunicaciones móviles, impulsando el desarrollo de algoritmos de gestión proactiva de la red. Para ello, se propone una selección de características bidimensional, en la que no sólo se seleccionan los KPI más relevantes para predecir otro KPI objetivo, sino también los instantes de tiempo más relevantes de cada KPI. Esta selección de características se realiza antes de la predicción. De este modo, el sistema propuesto mejora la precisión de la predicción y reduce la complejidad de los modelos predictivos obtenidos.
- Para validar el rendimiento del mecanismo propuesto, se han realizado baterías de pruebas utilizando algoritmos de predicción de diferente complejidad (LR, SVR y GRU). Además, se ha analizado el impacto de utilizar

el mecanismo propuesto para predecir diferentes instantes de tiempo en el futuro.

- El rendimiento del algoritmo se ha comparado con otras soluciones propuestas en el estado del arte, demostrando así que el mecanismo propuesto es capaz de conseguir mejores resultados.

Obj. 4: Proponer un mecanismo de modelado de redes de prueba.

- Siguiendo con este objetivo, en esta tesis se ha diseñado un método que permite el modelado de redes de prueba de forma que imiten el comportamiento de redes reales o zonas de éstas desde la perspectiva del UE. De esta forma, se pretende obtener una red de pruebas con la configuración necesaria para realizar pruebas de concepto de algoritmos de gestión de redes en un entorno con un comportamiento lo más parecido posible a una red real. Desde el conocimiento de los autores, en el estado del arte no existen otros trabajos relacionados con el modelado de redes de pruebas.
- La realización del modelado desde el punto de vista del UE permite obtener una visión E2E del comportamiento de la red. Con este objetivo, se han utilizando métricas como RSRP y *throughput*. Así, el objetivo del método propuesto es conseguir que los UE conectados a la red de pruebas obtengan valores de RSRP y *throughput* similares a los de los UE conectados a la red comercial a imitar. Para ello, el método propuesto realiza un ajuste automático de diferentes parámetros de configuración de la red de pruebas.
- Para evaluar el método de modelado se han realizado pruebas en la red UMAHetNet, utilizando como entrada los resultados de una campaña de medidas realizada en las redes de algunos de los principales operadores europeos en el marco del proyecto MONROE.

Obj. 5: Estudiar el impacto del ajuste de los parámetros de configuración de RLC en la QoE.

- Se ha realizado un análisis sobre el impacto del ajuste de los parámetros de configuración de la capa RLC en la QoE de los usuarios. El análisis realizado presenta un mayor nivel de detalle que otros encontrados en el estado del arte. Así, los dos modos de funcionamiento de la capa RLC: AM y UM, han sido estudiados. Para ello, se han utilizado dos de los servicios más comunes en una red móvil: la transferencia de archivos y la tranmsisión de vídeo. Cada uno de estos servicios utiliza un modo de funcionamiento RLC diferente. Además, se estudian más parámetros de configuración que en trabajos anteriores, lo que permite obtener una mejor comprensión del funcionamiento de esta capa. Otra contribución relacionada con este trabajo es el análisis del efecto de las configuraciones de RLC en la QoE.

- El estudio se ha realizado en un entorno LTE simulado. Como resultado de este estudio, se obtienen una serie de recomendaciones para la configuración de la capa RLC en LTE. Debido a las similitudes entre las capas RLC de las tecnologías LTE y 5G, este análisis podría reproducirse en redes 5G, obteniendo así recomendaciones para la configuración de la capa RLC en esta tecnología.
- Finalmente, este estudio demuestra la posibilidad de mejorar la QoE a través de la configuración de la capa RLC, abriendo así el camino al desarrollo de algoritmos para ajustar automáticamente la configuración de esta capa.

Obj. 6: Proponer un algoritmo para la mejora de la QoE basado en el ajuste de los parámetros de configuración de RLC.

- La capa RLC es la responsable de proporcionar un enlace fiable para la transmisión de datos, por lo que tiene un gran impacto en la QoE percibida por los usuarios. A pesar de ello, la optimización de la QoE basada en el ajuste de la capa RLC no ha sido abordada en el estado del arte. En esta tesis se ha desarrollado un algoritmo para maximizar la QoE percibida por los usuarios mediante el ajuste de los parámetros de configuración de la capa RLC. Este algoritmo tiene como objetivo configurar automáticamente la capa RLC para proporcionar la mejor QoE posible a los usuarios de diferentes tipos de servicios. Así, este trabajo amplía el estudio realizado en respuesta al Obj. 5.
- Las pruebas de evaluación del algoritmo se han realizado tanto en un entorno LTE simulado como en una red real de pruebas. Las pruebas realizadas cubren la optimización de dos servicios diferentes: la transferencia de archivos y la transmisión de vídeo. Además, estas pruebas se han realizado bajo diferentes condiciones de ancho de banda disponible en la red. Las pruebas muestran que el algoritmo propuesto es capaz de converger a los valores máximos de QoE en cada situación, existiendo una dependencia entre los valores de los parámetros de configuración de la capa RLC y las

condiciones de la red.

Obj. 7: Proponer un algoritmo de activación de la MC para el caso de uso de AGV en un entorno industrial.

- Se ha diseñado un algoritmo para la activación automática y dinámica del DC para el caso de uso de AGV en un entorno industrial exterior. Este algoritmo se basa en la QoS y en la diferencia de RSRP entre las celdas primarias y secundarias para tomar decisiones sobre cuándo activar o desactivar el DC. Las decisiones se toman de forma independiente para cada AGV.
- Para su correcto funcionamiento, los AGV transmiten imágenes de vídeo en tiempo real a su sistema central de control de guiado, del que reciben órdenes de control. Así, en este caso de uso, el enlace ascendente está mucho más cargado que el descendente. Por esta razón, y a diferencia de la mayoría de los trabajos del estado del arte, este algoritmo se centra en la gestión del DC del enlace ascendente. En concreto, el esquema de DC propuesto es la combinación de dos portadoras en un único canal agregado de un AGV hacia dos nodos de la red.

Obj. 8: Proponer un algoritmo de optimización proactiva para evitar degradaciones de rendimiento en el caso de uso de AGV en un entorno industrial.

- Debido a la criticidad de las comunicaciones de los AGV con su sistema de control de guiado central, se considera necesario realizar una gestión proactiva que permita actuar de forma temprana ante posibles degradaciones de rendimiento. Así, al algoritmo anterior se le ha añadido una etapa de predicción, dando lugar a un único algoritmo en el que la activación del DC se realiza de forma proactiva. De este modo, las decisiones de activación o desactivación del DC se basan en la QoS predicha. Para la predicción de la QoS se propone un esquema sencillo basado en el uso de un algoritmo de *clustering* y una regresión logística, facilitando así la integración del algoritmo en herramientas reales de gestión de red.
- La evaluación del algoritmo se ha realizado en un entorno simulado. En concreto, se ha implementado un simulador basado en un escenario industrial real en el que actualmente se utilizan AGV para realizar determinadas

tareas. En el escenario actual el número de AGV es limitado, se mueven a baja velocidad y están equipados con tecnología LTE, utilizando una red pública. En este trabajo, se propone la implementación de una red privada 5G, que permitirá aumentar el número de AGV conectados a la red y la velocidad a la que se mueven por el escenario.

- El algoritmo propuesto ha sido evaluado a dos niveles: precisión de la predicción de la QoS y rendimiento radioeléctrico en términos de ganancia de QoS. Además, el rendimiento del algoritmo se ha comparado con dos líneas de base. Los resultados muestran que los beneficios del algoritmo propuesto en términos de mejora del rendimiento del enlace ascendente y de reducción de la señalización son especialmente relevantes en escenarios de carga media-baja. Así, se demuestra que el algoritmo propuesto es más robusto que las líneas base (cuyo rendimiento se basa en la autocorrelación de la QoS) ante cambios en el entorno radioeléctrico y las condiciones de interferencia.

A.3.2 Publicaciones

Revistas

Publicaciones derivadas de esta tesis

[I] J. Mendoza, I. de-la-Bandera, C.S. Álvarez-Merino, E.J. Khatib, J. Alonso, S. Casalderrey-Díaz, and R. Barco, "5G for Construction: Use Cases and Solutions," *Electronics*, vol. 10, no. 14, p. 1713, Jul. 2021.

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[VII] I. de-la-Bandera, D. Palacios, J. Mendoza, and R. Barco, "Feature Extraction for Dimensionality Reduction in Cellular Networks Performance Analysis," *Sensors*, vol. 20, no. 23, p. 6944, Dic. 2020.

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Conferencias

Conferencias derivadas de esta tesis

[XI] J. Mendoza, I. de-la-Bandera, J. Burgueño, C. Morillas, D. Palacios, and R. Barco, "Anomaly Detection and Analysis Framework for Mobile Networks," en *2021 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit)*, Oporto (Portugal), Jun. 2021.

[XII] J. Mendoza, D. Palacios, I. de-la-Bandera, and R. Barco, "Selección Automática de Características para una Gestión Proactiva Eficiente de Redes 5G," en *XXXIV*

Simposium Nacional de la Unión Científica Internacional de Radio (URSI 2019), Sevilla (España), Sep. 2019.

Conferencias relacionadas con esta tesis

[**XIII**] A. Herrera-García, S. Fortes, E. Baena, J. Mendoza, and R. Barco, "Modelado de Indicadores de Calidad de Servicio para la Gestión de red Extremo a Extremo," en *XXXIV Simposium Nacional de la Unión Científica Internacional de Radio (URSI 2019)*, Sevilla (España) Sep. 2019.

A.3.3 Proyectos relacionados

Esta tesis ha sido funanciada por el Ministerio de Ciencia, Innovación y Universidades en el marco del acuerdo FPU18/04786.

Esta tesis también ha contribuido a los siguientes proyectos:

- Proyectos internacionales:
  - MONROE: Measuring Mobile Broadband Networks in Europe, financiado por: H2020-ICT-11-2014, número de proyecto: 644399.
  - ONE5G: E2E-aware Optimizations and advancements for the Network Edge of 5G New Radio, financiado por H2020-ICT-2016-2, número de proyecto: 760809.
- Proyectos nacionales:
  - NEREA: Network Strategy And Evolution Advisor, financiado por el Ministerio de Economía y Competitividad y el Fondo Europeo de Desarrollo Regional (FEDER), número de proyecto: RTC-2017-6661-7.
  - PENTA: Provisión de servicios PPDR a través de Nuevas Tecnologías de Acceso radio, financiado por la Junta de Andalucía y FEDER, número de proyecto: PY18-4647.
  - DAMA5G: Detección de Anomalías Multivariable Asistida, financiado por la Junta de Andalucía and ERDF, número de proyecto: UMA-CEIATECH-11.
  - TEDES5G: Técnicas 5G para una Edificación Eficiente y Segura, financiado por la Junta de Andalucía y FEDER, número de proyecto: UMACEIATECH-12

- MUSE: Massive USer Experience Assessment and Prediction for Mobile Networks, financiado por la Junta de Andalucía y FEDER, número de proyecto: UMA-CEIATECH-13.
- Métodos de planificación y optimización de la calidad de experiencia en redes B4G, financiado por el Ministerio de Economía y Competitividad, número de proyecto: TEC2015-69982-R.
- Gestión integral avanzada de funciones SON para redes móviles futuras, Proyectos de Execelencia, Junta de Andalucía, número de proyecto: P12-TIC-2905.
- MICROSOL: Microintercambiadores solares inteligentes: Prototipo de arquitecturas del sol para la movilidad sostenible de la UMA, financiado por el Plan I de Smart-Campus de la Universidad de Málaga.

A.3.4 Estancia de investigación

Como parte de esta tesis se ha realizado una estancia de investigación de seis meses en Aalborg (Dinamarca), colaborando con la Universidad de Aalborg y Nokia-Bell Labs Aalborg en la gestión proactiva de la funcionalidad DC en un entorno industrial. La estancia tuvo lugar entre septiembre de 2020 y febrero de 2021 y fue supervisada por István Z. Kovács y Troels B. Sørensen.

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