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Tesis Doctoral

Self-Organizing Networks use cases in commercial deployments

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Ingeniería de Comunicaciones

Autorización para la lectura de la Tesis Doctoral

Por la presente, Dra. Dª. Raquel Barco Moreno, profesora doctora del Departamento de Ingeniería de Comunicaciones de la Universidad de Málaga y Dr. D. Juan Jesús Sánchez Sánchez, mánager del departamento de "*BMAS NDO Continuous Analysis*" de la empresa Ericsson, certifican que el doctorando Omar Kaddoura Marín, Ingeniero de Telecomunicación, ha realizado bajo su dirección en el Departamento de Ingeniería de Comunicaciones de la Universidad de Málaga en colaboración con la empresa Ericsson, el trabajo de investigación correspondiente a su TESIS DOCTORAL titulada:

"Self-Organizing Networks use cases in commercial deployments"

En dicho trabajo se han propuesto aportaciones originales para diversos problemas de auto-organización en redes móviles comerciales. Los resultados expuestos han dado lugar a las siguientes publicaciones en revistas, aportaciones a congresos internacionales y solicitud de patente que no han sido utilizadas en tesis anteriores.

1. O. Kaddoura et al, "Greenfield Design in 5G FWA Networks", IEEE Communications Letters, vol. 23, no. 12, pp. 2422-2426, Dec. 2019, doi: 10.1109/LCOMM.2019.2939470.
2. O. Kaddoura, J. Outes, J. J. Sánchez-Sánchez, R. Barco, "Radio Frequency Footprint Characterization Based on Mobility Indicators", IEEE Wireless Communications Letters, Sep. 2020, doi: 10.1109/LWC.2020.3023283.
3. O. Kaddoura, R. Barco, I. Serrano, J. J. Sánchez-Sánchez, "Swapped Sectors Detection Based on Mobility Statistics", IEEE Communications Letters, vol. 22, no. 5, pp. 1038-1041, May 2018, doi: 10.1109/LCOMM.2018.2808292.
4. O. Kaddoura, J. J. Sánchez-Sánchez, I. Serrano, R. Barco, "Swapped Sectors Detection on Multi-Layer Networks", IEEE Communications Letters, vol. 22, no. 11, pp. 2342-2345, Nov. 2018, doi: 10.1109/LCOMM.2018.2867846.
5. O. Kaddoura, J. J. Sánchez-Sánchez, I. Serrano, R. Barco, "Swapped Sectors Detection Based on User Location During Inter-Site Handovers", IEEE Access, vol. 7, pp. 92547-92560, 2019, doi: 10.1109/ACCESS.2019.2927607.
6. O. Kaddoura, I. Serrano, J. J. Sánchez-Sánchez, R. Barco, "Edge Sectors Detection in Mobile Communications Networks", 2019 European Conference on Networks and Communications (EuCNC), Valencia, Spain 2019, pp. 586-591, doi: 10.1109/EuCNC.2019.8801977.
7. O. Kaddoura, I. Serrano, R. Barco, "Detección de sectores borde en redes de comunicaciones móviles", XXIV Simposium nacional de la Unión Científica Internacional de Radio, Valencia, 2014.
8. O. Kaddoura, J. Outes, G. Payo, "Method and Apparatus for Characterizing a Radio Frequency Environment in a Telecommunications Network", 03.10.2019, PCT/EP2018/057995.

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

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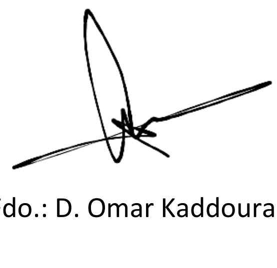

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para juzgar la Tesis Doctoral titulada "*Self-Organizing Networks use cases in commercial deployments*", realizada por D. Omar Kaddoura Marín y co-dirigida por la Dra. Raquel Barco Moreno y el Dr. D. Juan Jesús Sánchez Sánchez, acordó por

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A mis padres.

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Han pasado años desde que comenzara mi andadura en el programa de doctorado de la Universidad de Málaga. Afortunadamente, y no de forma casual, este hecho coincidió con mi incorporación a la plantilla de Ericsson, empresa que hoy considero mi familia. Allí, he conocido a una gran cantidad de personas, muchas de las cuáles hoy en día considero mis amigos. No ha sido sencillo compaginar la exigencia de una empresa puntera como es Ericsson con la atención y mimos que requiere la realización de una tesis doctoral. Sin embargo, aquí me encuentro, redactando las últimas líneas de un trabajo que ha resultado mucho más que una meta profesional, pues se ha convertido en toda una enseñanza de vida. Si bien la escritura de un documento no es algo sencillo, estas líneas son fáciles de teclear, pues salen directas desde mi corazón con la intención de dar las gracias a todos aquellos que, de una forma u otra, me han ayudado a completar este trabajo.

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Carrying out a Ph.D. thesis outside of a university research group is not easy. Luckily, whenever I have needed it, I have had the help of great researchers such as Ana Gómez, Isabel de la Bandera, Alejandro Aguilar and Rocío Acedo. Many thanks to you all.

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Summary

Since their origins, mobile communication networks have undergone major changes imposed by the need for networks to adapt to user demand. To do this, networks have had to increase in complexity. In turn, complexity has made networks increasingly difficult to design and maintain. To mitigate the impact of network complexity, the concept of self-organizing networks (SON) emerged. Self-organized networks aim at reducing the complexity in the design and maintenance of mobile communication networks by automating processes. Thus, three major blocks in the automation of networks are identified: self-configuration, self-optimization and self-healing.

This thesis contributes to the state of the art of self-organized networks through the identification and subsequent resolution of a problem in each of the three blocks into which they are divided.

With the advent of 5G networks and the speeds they promise to deliver to users, new use cases have emerged. One of these use cases is known as Fixed Wireless Access. In this type of network, the last mile of fiber is replaced by broadband radio access of mobile technologies. Until now, regarding self-configuration, greenfield design methodologies for wireless networks based on mobile communication technologies are based on the premise that users have mobility characteristics. However, in fixed wireless access networks, the antennas of the users are in fixed locations. Therefore, this thesis proposes a novel methodology for finding the optimal locations were to deploy network equipment as well as the configuration of their radio parameters in Fixed Wireless Access networks.

Regarding self-optimization of networks, current algorithms make use of signal maps of the cells in the network so that the changes that these maps would experience after modifying any network parameter can be estimated. In order to obtain these maps, operators use predictive models calibrated through real network measurements. These measurements can be obtained from different sources, but these sources are either expensive or not applicable to any network. To solve this problem, this thesis proposes a method that uses information available in any network so that the calibration of predictive maps is converted into universal without losing accuracy with respect to current methods.

Furthermore, the complexity of today's networks makes them prone to failure. To save costs, operators employ network self-healing techniques so that networks are able to self-diagnose and even self-fix when possible. Among the various failures that can occur in mobile communication networks, a common case is the existence of sectors whose radiated signal has been exchanged. This issue appears during the network roll-out when engineers accidentally cross feeders of several antennas. Currently, manual methodology is used to identify this problem. Therefore, this thesis presents an automatic system to detect these cases.

Finally, special attention has been paid to the computational efficiency of the algorithms developed in this thesis since they have finally been integrated into commercial tools.

Resumen

Desde sus orígenes, las redes de comunicaciones móviles han experimentado grandes cambios impuestos por la necesidad de las redes a adaptarse a la demanda de los usuarios. Para ello, las redes han tenido que aumentar en complejidad. A su vez, el aumento en la complejidad ha provocado que las redes sean cada vez más difíciles de diseñar y mantener. Para mitigar el impacto de la complejidad de las redes, surgió el concepto de redes auto-organizadas (*Self-Organizing Networks* (SON) en inglés). Las redes auto-organizadas pretenden disminuir la complejidad en el diseño y mantenimiento de las redes de comunicaciones móviles mediante la automatización de procesos. Así, se identifican tres grandes bloques en la automatización de las redes: la auto-configuración, la auto-optimización y la auto-curación.

Esta tesis contribuye al estado del arte de las redes auto-organizadas a través de la identificación y posterior resolución de un problema en cada uno de los tres bloques en que éstas están divididas.

Con la llegada de las redes 5G y las velocidades que éstas prometen entregar a los usuarios, han surgido nuevos casos de uso. Uno de estos casos de uso se conoce como redes de acceso inalámbrico fijo (*Fixed Wireless Access* en inglés). En este tipo de red, se sustituye el último tramo de fibra óptica hasta el domicilio del abonado por el acceso radio de banda ancha de tecnologías móviles. Hasta ahora, en lo referente a la auto-configuración, las metodologías de diseño de redes inalámbricas basadas en tecnologías de comunicaciones móviles partían de la premisa de que los usuarios presentan características de movilidad. Sin embargo, en las redes de acceso inalámbrico fijo, las antenas de los usuarios se encuentran en emplazamientos fijos. Por tanto, esta tesis propone un método novedoso para

el diseño óptimo de los emplazamientos de los equipos en este tipo de redes y de la configuración de sus parámetros radio.

Respecto a la auto-optimización de redes, los algoritmos actuales hacen uso de mapas de señal de las celdas que componen la red de modo que puedan estimar los cambios que experimentarían estos mapas tras la modificación de cualquier parámetro de red. Con el objetivo de obtener estos mapas, los operadores utilizan modelos predictivos calibrados a través de medidas reales de la red. Estas medidas se pueden obtener a través de distintas fuentes, pero estas fuentes son o bien costosas o no aplicables a cualquier red. Para solucionar este problema, esta tesis propone un método que utiliza información disponible en cualquier red de forma que la calibración de mapas predictivos sea de carácter universal sin perder precisión con respecto a los métodos actuales.

Por otra parte, la complejidad de las redes actuales hace que éstas sean propensas a fallos. Para ahorrar costes, los operadores emplean técnicas de auto-curación de redes de forma que éstas sean capaces de auto-diagnosticarse e incluso sanarse cuando es posible. Entre los diversos fallos que se pueden producir en las redes de comunicaciones móviles, un caso común es el de la existencia de sectores cuya señal radiada ha sido intercambiada por la de otros. Esto se debe a fallos en la instalación por parte de los ingenieros que, accidentalmente, cruzan los cables con los que se alimentan las antenas. La metodología actual para la identificación de este problema es de carácter manual, de modo que esta tesis propone un sistema automático que permita detectar estos casos.

Por último, se ha prestado especial atención a la eficiencia computacional de los algoritmos desarrollados en esta tesis ya que éstos han sido finalmente integrados en herramientas comerciales.

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Acronyms

2G	**2**nd **G**eneration
3G	**3**rd **G**eneration
4G	**4**th **G**eneration
3GPP	**3**rd **G**eneration **P**artnership **P**roject
5G	**5**th **G**eneration
5G NSA	**5G** **N**on **S**tand**A**lone
5G SA	**5G** **S**tand**A**lone
5GC	**5G** **C**ore Network
5GS	**5G** **S**ystem
ACP	**A**utomatic **C**ell **P**lanning
AF	**A**pplication **F**unction
AMF	**A**ccess and Mobility **M**anagement **F**unction
ANR	**A**utomatic **N**eighbor **R**elation
AUSF	**Au**thentication **S**erver **F**unction
BBU	**B**ase**b**and **U**nit
BS	**B**ase **S**tation
CAPEX	**Cap**ital **Ex**penditures
CM	**C**onfiguration **M**anagement
CMC	**C**onnection **M**obility **C**ontrol
CPE	**C**ustomer **P**remises **E**quipment
DHCP	**D**ynamic **H**ost **C**onfiguration **P**rotocol

DL	**D**own**l**ink
DRB	**D**ata **R**adio **B**earer
DT	**D**rive **T**est
EARFCN	**E**-UTRA **A**bsolute **R**adio **F**requency **C**hannel **N**umber
EDGE	**E**nhanced **D**ata Rates for **G**SM **E**volution
EM	**E**lement **M**anager
eMBB	**E**nhanced **M**obile **B**road**b**and
eNB	**E**-UTRAN **N**ode **B**
eNodeB	**E**-UTRAN **N**ode **B**
EPC	**E**volved **P**acket **C**ore
EPS	**E**volved **P**acket **S**ystem
E-RAB	**E**-UTRAN **R**adio **A**ccess **B**earer
E-UTRAN	**E**volved **U**niversal **T**errestrial **R**adio **A**ccess **N**etwork
FWA	**F**ixed **W**ireless **A**ccess
GERAN	**G**SM/**E**DGE **R**adio **A**ccess **N**etwork
GLONASS	**Glo**bal'naya **Na**vigatsionnaya **S**putnikovaya **S**istema
gNB	Next **g**eneration **N**ode **B**
gNB-CU	Next **g**eneration **N**ode **B** **C**ontrol **U**nit
gNB-DU	Next **g**eneration **N**ode **B** **D**istributed **U**nit
GPS	**G**lobal **P**ositioning **S**ystem
GSM	**G**lobal **S**ystem for **M**obile Communications
HSPA	**H**igh **S**peed **P**acket **A**ccess
HSS	**H**ome **S**ubscriber **S**erver
IMSI	**I**nternational **M**obile **S**ubscriber **I**dentity
IoT	**I**nternet **o**f **T**hings
IP	**I**nternet **P**rotocol
IPSec	**I**nternet **P**rotocol **Sec**urity
KPI	**K**ey **P**erformance **I**ndicator
LTE	**L**ong **T**erm **E**volution

LWA	**L**TE-**W**LAN **A**ggregation
LWIP	**L**TE-**W**LAN integration with **IP**Sec tunnel
MDT	**M**inimization of **D**rive **T**ests
MIMO	**M**ultiple-**I**nput **M**ultiple-**O**utput
MME	**M**obility **M**anagement **E**ntity
mMTC	**M**assive **M**achine **T**ype **C**ommunications
mmWaves	**M**illi**m**eter **Waves**
MR	**M**easurement **R**eport
MT	**M**obile **T**races
NAS	**N**on **A**ccess **S**tratum
ng-eNB	**N**ext **G**eneration **E**-UTRAN **N**ode **B**
NGMN	**N**ext **G**eneration **M**obile **N**etworks
NG-RAN	**N**ext **G**eneration **RAN**
NR	**N**ew **R**adio
NSSAAF	**N**etwork **S**lice **S**pecific **A**uthentication and **A**uthorization **F**unction
NSSF	**N**etwork **S**lice **S**election **F**unction
OFDM	**O**rthogonal **F**requency-**D**ivision **M**ultiplexing
OFDMA	**O**rthogonal **F**requency-**D**ivision **M**ultiple **A**ccess
OPEX	**Op**erational **Ex**penditures
OSS	**O**perations **S**upport **S**ystem
PCF	**P**olicy **C**ontrol **F**unction
PCI	**P**hysical **C**ell **I**dentity
PDCP	**P**acket **D**ata **C**onvergence **P**rotocol
PEE	**P**ower, **E**nergy and **E**nvironmental
P-GW	**P**acket Data Network **G**ate**w**ay
PM	**P**erformance **M**anagement
PRACH	**P**hysical **R**andom **A**ccess **Ch**annel
PS	**P**acket **S**witched
QoS	**Q**uality **o**f **S**ervice

RAC	**R**adio **A**dmission **C**ontrol
RAT	**R**adio **A**ccess **T**echnology
RBC	**R**adio **B**earer **C**ontrol
RF	**R**adio **F**requency
RRM	**R**adio **R**esource **M**anagement
RSRP	**R**eference **S**ignal **R**eceived **P**ower
RSRQ	**R**eference **S**ignal **R**eceived **Q**uality
RSS	**R**eceived **S**ignal **S**trength
RSSI	**R**eceived **S**ignal **S**trength **I**ndicator
RU	**R**adio **U**nit
SC-FDMA	**S**ingle **C**arrier **F**requency-**D**ivision **M**ultiple **A**ccess
SDU	**S**ervice **D**ata **U**nit
S-GW	**S**erving **G**ate**w**ay
SMF	**S**ession **M**anagement **F**unction
SON	**S**elf-**O**rganized **N**etworks
SRVCC	**S**ingle **R**adio **V**oice **C**all **C**ontinuity
TA	**T**iming **A**dvance
TD-SCDMA	**T**ime **D**ivision **S**ynchronous **C**ode **D**ivision **M**ultiple **A**ccess
UDM	**U**nified **D**ata **M**anagement
UE	**U**ser **E**quipment
UL	**U**p**l**ink
UMTS	**U**niversal **M**obile **T**elecommunications **S**ystem
UPF	**U**ser **P**lane **F**unction
URLLC	**U**ltra **R**eliable **L**ow **L**atency **C**ommunications
UTRAN	**U**niversal **T**errestrial **R**adio **A**ccess **N**etwork
WLAN	**W**ireless **L**ocal-**A**rea **N**etwork
WT	**W**alk **T**est

Chapter 1

Introduction

This first chapter introduces the research activity done in this thesis. Firstly, the motivation that led to this investigation is presented along with the significance of the topics studied. Secondly, the main objectives that this thesis pursues are presented. Finally, this chapter also describes the structure of this document.

1.1 Motivation

Over the years, the field of mobile communication has experienced a vast growth. Mobile devices have changed from their origins and, nowadays, they are not only a mere mean to communicate people. Since they have access to the Internet, they are used for activities like watching videos, remote controlling, sensing, reading books, shopping, data storage in the cloud or learning. In addition, with the advent of the Internet of Things (IoT), the number of subscribers has increased. In 2019, they exceed 8 billion and represent 108% of global penetration [1]. Thus is, there are more subscribers than inhabitants in Earth.

The emergence of new mobile devices demanding new services has forced mobile technologies to evolve, which lead to a higher complexity of mobile networks. Mobile networks must support high throughput demand, massive connectivity and low latency while keeping high the Quality of Service (QoS) demanded by users.

Nowadays, the most advanced commercial technology of mobile communication networks is governed by 5^{th} Generation (5G) networks [2].

Due to the complexity of modern networks, mobile operators are forced to invest a large amount of resources both in deployment and maintenance phases. Moreover, market competitiveness adds pressure to mobile operators, who need to reduce the prices of their products. Therefore, in order to ensure the profitability of their projects, mobile operators aim at ensuring the minimization of Capital Expenditures (CAPEX) and Operational Expenditures (OPEX). Namely, mobile operators must achieve a balance between maximizing profits with lower prices and delivering high-quality services to their subscribers.

In this context, Next Generation Mobile Networks (NGMN) alliance specified Self-Organized Networks (SON) as a solution for automating the planning, deployment, optimization and maintenance of Long Term Evolution (LTE) mobile networks [3, 4]. Later, the 3^{rd} Generation Partnership Project (3GPP) incorporated the ideas of SON and applied them to their standards [5]. This concept was introduced by pursuing the augmentation of the network intelligence so that manual tasks are automated, thus reducing costs. Since SON were firstly introduced, they have become a mandatory requirement in mobile communication networks and a continuous topic of research [6, 7, 8, 9, 10, 11].

Particularly, 3GPP divided SON functionalities into three main categories [5, 12]:

- Self-configuration [13]. Self-configuration is divided into planning and deployment phases.
  - Planning phase consists in the design of new elements to be added to the network. This is, finding the location where these will be added and the configuration of their parameters so that network coverage, capacity and interference are optimum.
  - Deployment phase pursues the automatic configuration of new elements added to the network as well as the existing ones. Namely, when a new base station (BS) is introduced into the network and powered on, it gets immediately recognized and registered.

- Self-optimization [13]. Since network conditions are stochastic due to changes in weather, traffic patterns or external interferences, self-optimization is responsible for adjusting network parameters so that optimum performance is always achieved. Self-optimization can be broken down into monitoring, analysis and action phases.
  - Monitoring: A series of indicators of network behavior are extracted.
  - Analysis: Changes in the parameters of the network are proposed based on the indicators of network behavior.
  - Action: The proposed changes on the network parameters are implemented.
- Self-healing [14]. Once networks are operating, these could suffer from performance degradation due to problems in the network software or hardware. Self-healing comprehends four phases to mitigate this.
  - Fault detection. Based on network performance statistics, a problem is detected.
  - Compensation. Actions are performed in order to mitigate the network performance degradation.
  - Fault diagnosis. The root cause of the problem is identified.
  - Repair. The problem that produced the degradation is corrected.

Because of the necessity of including SON concepts to mobile communication networks, various projects were launched to research, develop and industrialize SON techniques in LTE and 5G networks. Among these, one can find UniverSelf [15], SELFNET [16], COMMUNE [17], SEMAFOUR [18], FP7 E3 [19], CELTIC Gandalf [20], FP7 SOCRATES [12], CSON [21], QSON [22] and SELFNET-5G [23]. However, despite all the research done in SON, there are still areas which need a deeper analysis either because they have not been covered in a proper extent or because, as the technology has continued evolving, new areas susceptible from automation have emerged. Examples of these areas can be found in every one of the SON categories. Further down, one area lacking further research is presented for each SON category.

In order to apply SON concepts to mobile communication networks, these networks provide insights like information about their configuration or their performance through different interfaces. These interfaces are widely known as Configuration Management (CM), Performance Management (PM) or Mobile Traces (MT). CM provides information about the configuration of the network such as cell locations, azimuth configurations, power configurations, handover thresholds, etc. PM provides information about the performance of the network. Performance information is usually aggregated at cell or relational level and contains values of multiple Key Performance Indicators (KPIs) such as number of calls, number of dropped calls, number of handovers, etc. Finally, MT provides information about the signaling messages sent between mobile devices and network elements. All these interfaces can be accessed through the Operations Support System (OSS) of the mobile network.

With the advent of 5G networks and the data rates they guarantee, Fixed Wireless Access (FWA) [24], designed to bring broadband Internet access to homes, have arisen as the best alternative to fixed technologies. FWA consists in replacing the last mile of cables by air interface so that a single network transceiver provides broadband service to multiple homes provided with specific Customer Premises Equipment (CPE). As part of self-configuration category in SON, the planning phase aims at finding the best network configuration to satisfy the subscribers data rate requirements while minimizing the cost of the network deployment. However, existing studies target at optimizing the radio frequency (RF) configuration for the whole household instead of only the spot where to install the antenna of the CPE. This leads to suboptimal networks in which coverage and interference performance are jeopardized.

As part of self-optimization functionalities, RF footprint is accurately modeled so that the effect that modifying network parameters has over the network performance can be determined in advance. Mobile operators frequently utilize empirical RF measurements taken through drive tests (DTs) or walk tests (WTs) [25] to generate RF footprint models since these provide higher accuracy than theoretical models. However, DTs are expensive and sometimes, mobile operators utilize MT [26] and Minimization of Drive Tests (MDT) [27, 28, 29, 30], which provide them with RF measurements and their corresponding location information. Nevertheless, these features are not always enabled in commercial networks and, in addition, their measurements may produce incomplete results due to the discretization in sample collection [31]. Consequently, mobile operators require a method capable of building complete RF footprint models based on standardized features instead of relying on functionalities that either are not available in commercial networks or their licenses are too expensive.

The roll-out of a mobile network is a process in which several actions are carried out. Some of these actions are performed by engineers and prone to human error. Consequently, the final network performance might be degraded if a mistake was made during the roll-out phase. A common error during the roll-out process is the case in which feeders from baseband units (BBUs) to radio units (RUs) or feeders from RUs to antennas are interchanged. In sectorized sites, this error, known as swapped sectors, leads to service areas of two or more co-sited cells to become swapped. Because of swapped sectors, deployed networks could present issues in coverage, interference or mobility procedures, among others. Currently, swapped sectors are detected through DTs and WTs [25]. In these, engineers perform measurements in the surroundings of sites in order to find the signal footprint from sectors that belong to them. Then, they compare the obtained footprint with the expected from the designed sectorization. This fault detection activity could be automated and included as part of self-healing category in SON.

Therefore, this thesis contributes to the state-of-the-art and increases SON functionalities by overcoming the limitations of the aforementioned use cases and thus, narrowing the gaps in network automation.

1.2 Challenges and objectives

The prime goal of this thesis is to overcome limitations in use cases that belong to every one of the categories that compose SON. Therefore, challenges and objectives of this thesis are grouped into three categories: self-configuration, self-optimization and self-healing. These challenges have been identified in collaboration with Ericsson Network Design and Optimization unit, whose engineers occasionally need to address problems for which a solution does not exist yet, as the ones addressed in this thesis.

In the context of self-configuration, mobile operators aim at designing networks capable of supporting the requirements of their subscribers and provide the best user experience. For this purpose, commonly, mobile operators focus on three KPIs: coverage, dominance and capacity. Coverage refers to the ability of the network to provide enough signal level to its subscribers so that they may be served. Dominance refers to the interference a subscriber experiences from non-serving cells. Ideally, a subscriber will not observe interference from neighboring cells except for areas in which coverage is compromised (these are the areas where mobility procedures are carried out). Capacity refers to the capability of the network to provide service to all the subscribers that require from system resources simultaneously. All coverage, dominance and capacity can be improved by adding more BSs to the network. However, the addition of BSs increases the cost of the network to be deployed. Therefore, mobile operators try to maximize the KPIs of the network while keeping to a minimum the number of network equipment required to guarantee a proper QoS. Currently, for designing their new deployments, mobile operators use planning tools that make use of RF propagation models and antenna patterns to estimate the signal footprint of any new BS to be deployed. These tools are valid for regular deployments of mobile networks where the subscribers are expected to move around.

However, planning tools have not been enhanced to support the design of 5G FWA networks. This challenge is tackled through two different objectives. **The first objective consists in searching the optimal location of BSs and CPEs to be deployed in the network** (Objective 1). This is, among all the locations where BSs can be installed and the locations in households where to install the antennas of the CPEs, those locations which minimize the required network equipment while maximizing the network KPIs will be found. **The second objective consists in finding the optimal configuration of network parameters such as the azimuth of the antennas, their mechanical tilts, electrical tilts or their transmission power** (Objective 2).

In the context of self-optimization, mobile operators continually execute performance optimizations to adapt mobile networks to the persistent changes of the RF environment. A common optimization exercise is named *radio frequency shaping*. Radio frequency shaping consists in modifying antenna parameters such as azimuths, mechanical tilts and electrical tilts so that the signal footprint of the cells in the network is modified and both coverage and interference performance indicators are improved. Computer assisted methods known as Automatic Cell Planning (ACP) [32] arose to help network engineers to perform these optimization activities. These methods implement metaheuristic optimization algorithms [33] to find the parameter configuration that results in the best network performance. These algorithms evaluate a system cost function based on the signal level received by every subscriber in the network from all the surrounding cells. Therefore, providing these algorithms with a complete RF propagation model that allows them to recompute the signal level received by a subscriber when an antenna parameter is modified is mandatory.

For this purpose, mobile operators frequently carry out DT campaigns [25] in which field engineers take measurements of signal levels received from cells in different areas of the network. However, models built from DT measurements are usually incomplete as they only include measurements in places where only subscribers driving a vehicle are considered but not pedestrian subscribers. In order to overcome this limitation mobile operators started to collect MT [26] to calibrate basic RF propagation models based on predictions [34]. Nevertheless, not all equipment manufacturers (also known as vendors) implement the required functionality to collect MT and, when they include it, its license cost is sometimes unaffordable. Therefore, this thesis will provide **a new approach to calibrate basic RF propagation models based on predictions by making use of standardized functionality available in all vendors at no additional cost** (Objective 3).

In the context of self-healing, mobile networks, as complex systems, are exposed to suffer from faults. Because of this, mobile operators must have mechanisms to identify these faults so that they can take actions to correct them. Usually, vendors include alarm systems to their equipment so that when a fault is produced the network administrator is notified. In addition, these alarms usually are raised by recommending a solution to the problem. There are cases where the network equipment is working as expected but, due to the behavior of the network subscribers, the performance of the network is degraded. In these cases, detecting that a problem is occurring in the network is as easy as checking that there is a degradation in the KPIs of the network. Nevertheless, there are some cases where an incorrect performance of the network could be unnoticed. These cases are those in which the problem existed since the network was initially deployed. In these cases, the mobile network can operate normally. However, the mobile network has a problem that, if corrected, would improve its performance. Self-healing mechanisms are designed to take corrective actions to solve or mitigate those issues. Swapped Sectors, in which the signal expected to be radiated by a given antenna is actually radiated by a different one, is one of those cases. This problem arises when network engineers interchange feeders from BBUs to RUs or feeders from RUs to antennas. A network with swapped sectors could experience degradation in mobility procedures due to wrong neighbor lists or Physical Cell Identity (PCI) conflicts, throughput degradation due to high interference issues or the increase of dropped calls due to coverage holes.

In order to detect swapped sectors, mobile operators usually carry out DT campaigns in which field engineers take measurements of the signal level around network BSs and compare them to the signal level expected if no swapped sectors existed. As a challenge, this thesis tries to find an automated solution based on network performance indicators in order to be able to detect swapped sectors with a high success rate and without the need of performing costly DT campaigns. **This thesis will approach the detection of swapped sectors by utilizing mobility statistics in LTE and 5G networks to compute the direction to which the signal of a cell is being radiated** (Objective 4).

The previous objective may be enhanced by **utilizing positioning techniques to identify the actual locations of the subscribers when a handover procedure is triggered** (Objective 6). For this purpose, **a novel positioning technique applicable to commercial LTE and 5G networks** will be studied in this thesis (Objective 5). The success rate of any detection technique can be measured in terms of the number of true and false positives and negatives. In particular, in the context of swapped sectors detection, reducing the number

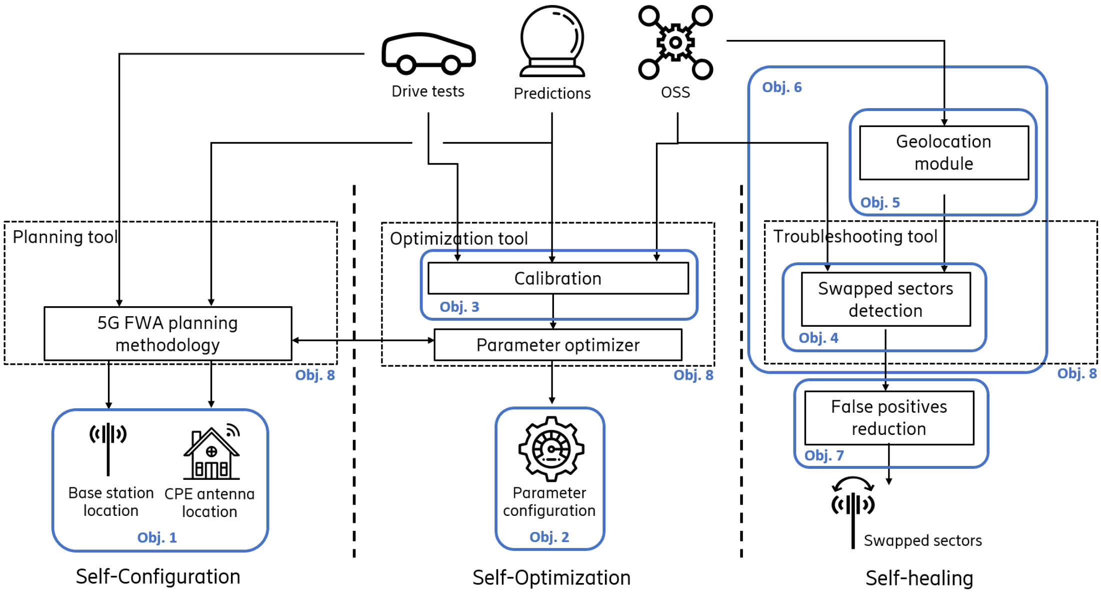

FIGURE 1.1: Objectives of this thesis.

of false positives is critical since fixing swapped sectors requires a visit to the BS location. Therefore, **a methodology will be investigated with the aim of reducing the number of false positives of the previous detection algorithm** (Objective 7).

All these objectives have in common the need of **solving problems in current commercial networks**. The solutions derived from this thesis will have to be simple so that they can be easily implemented in commercial networks without the need of making any changes in the network equipment.

Finally, **since Ericsson Network Design and Optimization unit uses proprietary tools in order to carry out design, optimization and troubleshooting exercises, all the solutions to the previous challenges will be integrated into these tools** (Objective 8) so that they can help mobile operators to automate processes and save costs.

These objectives are depicted in Fig. 1.1.

Summarizing, the objectives that will address the previous challenges are the following:

- Objective 1. To find the optimal locations where to deploy the network BSs and the antennas of the CPEs in 5G FWA networks. These locations will be selected to provide the best possible figure for the considered network performance indicators.

- Objective 2. To find a methodology that improves the state-of-the-art techniques for selecting the configuration of antenna parameters such as azimuth, electrical tilt or mechanical tilt that maximizes the performance in 5G FWA networks.

- Objective 3. To develop a methodology that calibrates RF propagation models based on predictions with the aim of using them in network optimization exercises. This methodology must be based on standardized functionalities available in any commercial LTE or 5G network.

- Objective 4. To design a framework capable of detecting swapped sectors. The proposed framework will find the actual antennas through which the signals of network cells are being radiated and will correlate these findings in order to detect cases in which feeders that connect RUs with antennas have been interchanged during the installation process. In order to do so, mobility indicators available in LTE and 5G networks will be used.

- Objective 5. To develop a technique capable of positioning subscribers in LTE and 5G networks with a higher precision than the current methods based on default functionalities.

- Objective 6. To combine Objective 4 and Objective 5 to improve the success rate of swapped sectors detection techniques.

- Objective 7. To find a methodology capable of reducing the number of false positives in swapped sectors detection.

- Objective 8. To implement all the methods, techniques and algorithms developed in this thesis in existing commercial planning, optimization and troubleshooting tools as part of the industrial mention of this thesis. Therefore, the proposed solutions will be validated with real data obtained from commercial networks.

1.3 Document structure

This document has been organized in seven chapters grouped in three main blocks (see Fig. 1.2). The first block presents the background and the knowledge required to understand the rest of this thesis. Chapter 1 details the challenges that motivate this thesis and the objectives that need to be accomplished in order to overcome them. Chapter 2 presents the state of the art. In this chapter, the challenges that need to be addressed are detailed so that the reader can later understand the solutions proposed in this thesis. Particularly, this chapter focuses in three use cases of SON that are not properly addressed with current technologies. Therefore, in this first block, several challenges in current technologies of self-organization, self-configuration and self-healing concepts are thoroughly presented as a prelude to the next block in which main objectives to overcome these challenges are studied.

Since this thesis is presented as a collection of articles ("*tesis por compendio de publicaciones*"), the second block of this document consists of the research papers related to the objectives previously presented in the first block. These papers are grouped in chapters according to their topic (Chapter 4 for self-configuration, Chapter 5 for self-optimization and Chapter 6 for self-healing). Nevertheless, aiming at guiding the reader through this block, this second block begins with Chapter 3, in which an outline of every paper is presented and the relations among all of them are clarified. Consequently, Chapter 3 consists of a complete summary of the research papers derived from this thesis and the research methodology followed in their achievement. Every one of the papers in this block illustrates the specific challenge presented in Section 1.2. to be addressed. Therefore, all papers detail the proposed solution to the problem they study and evaluate the main results of the associate research. Moreover, in addition to Chapter 2, each paper thoroughly explains its state of the art.

Chapter 4 is composed of a publication that proposes a solution to Objective 1 and Objective 2. In this publication, a novel optimization cost function that not only finds the optimal locations of network BSs but also the optimal locations of the antennas of the CPEs is presented. In addition, this publication proposes an

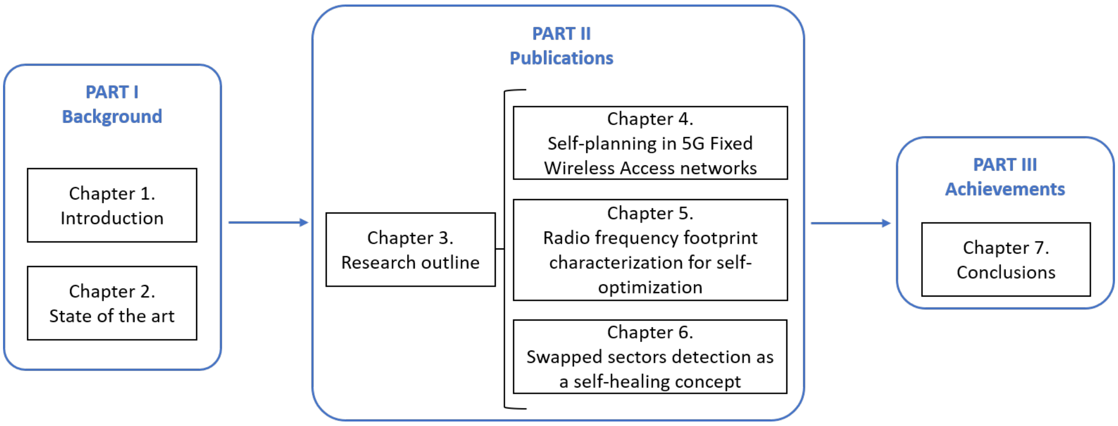

FIGURE 1.2: Document structure.

algorithm that combines both network planning and network configuration phases to find the optimal parameter configuration.

Chapter 5 is composed of a publication that addresses Objective 3. In this publication, a method to characterize the radio frequency footprint using network configuration and performance measurements is presented.

Chapter 6 is composed of 4 publications. The first two publications propose novel techniques in order to detect swapped sectors in mobile communication networks. The first one of these two publications presents a methodology that utilizes network indicators such as inter-site mobility statistics in order to compute actual azimuths. The second one of these two publications proposes a methodology that, instead of utilizing inter-site mobility statistics, utilizes intra-site and inter-frequency mobility statistics to find unexpected mobility patterns. These two publications address Objective 4. Additionally, Chapter 6 includes a publication that addresses Objective 5 by proposing a novel positioning methodology that improves current positioning technologies applicable to any commercial LTE and 5G network. Subsequently, this publication utilizes this positioning technique to enhance the methodology to detect swapped sectors presented in the first publication of this chapter. Therefore, Objective 6 is also addressed in this publication. Finally, the last publication of this chapter addresses Objective 7 by detecting sectors of a mobile network located at its boundaries and pointing outside of it.

Finally, the third and last block consists of Chapter 7. In this chapter the results obtained in this thesis are outlined and the main conclusions are discussed. Furthermore, future lines of research are also presented in this chapter.

Additionally, this document includes an appendix that contains a summary of this document in Spanish.

Chapter 2

State of the art

This chapter introduces the reader to those aspects needed to follow the contents of this thesis. The first section summarizes the topics of LTE technology related to this thesis, paying special attention to Radio Resource Management (RRM) and PM. The second section presents 5G technology as the evolution of LTE. The third section describes in detail the three concepts of SON: self-configuration, self-optimization and self-healing. Finally, the last section of this chapter covers the state of the art of the methodologies used to cope with the challenges identified in this thesis.

2.1 LTE Overview

LTE technology arose as a revolution of 2^{nd} Generation (2G) technologies like Global System for Mobile Communications (GSM) and Enhanced Data Rates for GSM Evolution (EDGE) as well as 3^{rd} Generation (3G) technologies like Universal Mobile Telecommunications System (UMTS) and High Speed Packet Access (HSPA). LTE was designed to use Orthogonal Frequency-Division Multiplexing (OFDM) [35] as the modulation mechanism. In this modulation, the channel bandwidth is divided into several parallel channels so that the bandwidth of each of these sub-channels is narrow enough to be considered as frequency-non-selective with flat frequency gain. All sub-channels in OFDM are orthogonal so

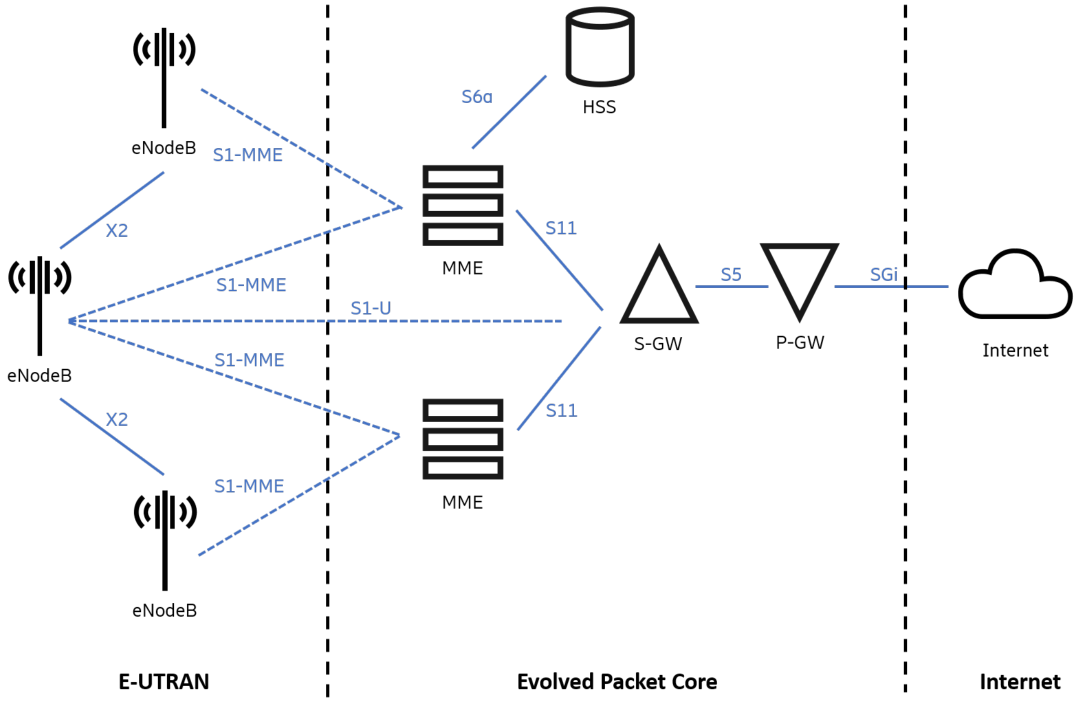

Figure 2.1: Evolved Packet system architecture.

that guard bands are not required, and the spectral efficiency is optimized. Particularly, Orthogonal Frequency-Division Multiple Access (OFDMA) and Single Carrier Frequency-Division Multiple Access (SC-FDMA) [36] are used as the multiple access techniques of downlink (DL) and uplink (UL) channel, respectively. With the use of OFDMA and SC-FDMA, LTE technology achieves lower latency figures and higher data rates.

In addition, LTE defines a new network architecture based on Packet Switched (PS) named Evolved Packet System (EPS) (see Fig. 2.1). This architecture is divided into the Evolved Packet Core (EPC) and the air interface known as Evolved Universal Terrestrial Radio Access Network (E-UTRAN).

The EPC is responsible for controlling the network access, managing mobility of subscribers and providing interconnection with other networks. The main elements of the EPC are:

- Mobility Management Entity (MME). This element has the following functions:

   - Generation and allocation of temporal identities to User Equipment (UE).
   - Idle state mobility management.
   - Roaming restrictions.
   - Non Access Stratum (NAS) signaling security key management.
   - Control plane for mobility between LTE and 2G/3G radio access networks.

- Serving Gateway (S-GW). This element is the user plane node connecting the EPC to the E-UTRAN. S-GW main functionality is:
   - Handling user data functions such as routing and forwarding packets.
   - Transport level packet marking in the UL and the DL.
   - Gathering accounting information per user and per bearer.
   - Collection of statistics required for charging.

- Packet Data Network Gateway (P-GW). This node connects the EPC to the internet. P-GW main functions are:
   - Allocation of Internet Protocol (IP) addresses for subscribers.
   - QoS enforcement.
   - Mobility anchor for non-3GPP radio access technologies.

- Home Subscriber Server (HSS). This is a central database that contains subscriber-related information. HSS functions include:
   - Mobility management.
   - Call and session establishment support.
   - Subscriber authentication.
   - Access authorization.

The main element that composes the E-UTRAN is the E-UTRAN Node B (abbreviated as eNodeB or eNB). This element is the evolution of UMTS NodeB and connects the network with the UE. The main functions of the eNodeB are:

- Radio resource management.
- Selection of MME at subscriber attachment.
- DL and UL admission control at bearer level.
- Header compression and user plane ciphering.
- Routing of user plane data towards S-GW.
- Measurement configuration for mobility and scheduling functions.

The eNodeB is connected to other eNodeBs and to the EPC using the next interfaces:

- X2. This interface connects to eNodeBs and is used to manage RRM procedures.
- S1-MME. This interface connects the eNodeB with the MME for control plane traffic.
- S1-U. This interface connects the eNodeB with the S-GW for user plane traffic.

2.1.1 Radio Resource Management

Since the behavior of a mobile channel can be modelled as a stochastic process, it is necessary to dynamically and efficiently manage the radio resources. The purpose of RRM [37] is to ensure the efficient use the available radio resources. RRM in E-UTRAN provides means to manage (e.g. assign, re-assign and release) radio resources taking into account single and multi-cell aspects. Particularly, main RRM functions are:

- Radio Admission Control (RAC). The task of RAC is to admit or reject the establishment requests for new radio bearers. In order to do this, RAC considers the overall resource situation in E-UTRAN, the QoS requirements, the priority levels and the provided QoS of in-progress sessions and the QoS requirement of the new radio bearer request. The goal of RAC is to ensure high radio resource utilization (by accepting radio bearer requests providing radio resources are available) and at the same time to ensure proper QoS for in-progress sessions (by rejecting radio bearer requests when they cannot be accommodated).

- Radio Bearer Control (RBC). The establishment, maintenance and release of radio bearers involve the configuration of radio resources associated with them. When setting up a radio bearer for a service, RBC considers the overall resource situation in E-UTRAN, the QoS requirements of in-progress sessions and the QoS requirement for the new service. RBC is also concerned with the maintenance of radio bearers of in-progress sessions at the change of the radio resource situation due to mobility procedures. Finally, RBC is also involved in the release of radio resources associated with radio bearers at session termination or handover procedures.

- Connection Mobility Control (CMC). CMC deals with the management of radio resources in relation to idle and connected mode mobility. Cell re-selection algorithms are used in idle mode whereas handover algorithms are used in connected mode. In LTE, both cell re-selection and handover algorithms are controlled by a set of events which determine when the UE should select a new cell or initiate a handover. Main mobility events in connected mode are [38] (see Fig. 2.2):

  - Event A1. This event indicates that serving cell becomes better than a threshold.
  - Event A2. This event indicates that serving cell becomes worse than a threshold.
  - Event A3. This event indicates that neighbor cell becomes offset better than serving cell.
  - Event A4. This event indicates that neighbor cell becomes better than a threshold.
  - Event A5. This event indicates that serving cell becomes worse than a threshold1 and neighbor cell becomes better than another threshold.

- Event B1. This event indicates that inter-Radio Access Technology (RAT) neighbor cell becomes better than a threshold.
- Event B2. This event indicates that serving cell becomes worse than a threshold and inter-RAT neighbor cell becomes better than another threshold.

The handover decision is taken based on the measurements performed by the UE (and eNodeB). In particular, the physical layer measurements considered in the mobility decisions are:

- Reference Signal Received Power (RSRP). RSRP is the linear average over the power contributions of the resource elements that carry cell-specific reference signals within the considered measurement frequency bandwidth.
- Reference Signal Received Quality (RSRQ). RSRQ is defined as (N x RSRP)/RSSI, where RSSI stands form Received Signal Strength Indicator and N is the number of resource blocks over the measurement bandwidth. RSSI contains all sorts of power (e.g. power from co-channel serving and non-serving cells, adjacent channel interference, thermal noise, etc.). Therefore, RSRQ indicates the portion of pure reference signal power over the whole power received by the UE.

In CMC, a target cell is selected by the E-UTRAN and the core network is only involved when the handover is successful. Packets are forwarded from the source cell to target cell in order to provide lossless handover. Additionally, KPIs (e.g., neighboring cell load, traffic distribution or hardware resources), and policies defined by operator can be considered by the eNodeB for selecting the target cell.

2.1.2 Performance Management

According to standards, LTE networks collect information about their performance [39]. Network elements of LTE networks collect and record performance

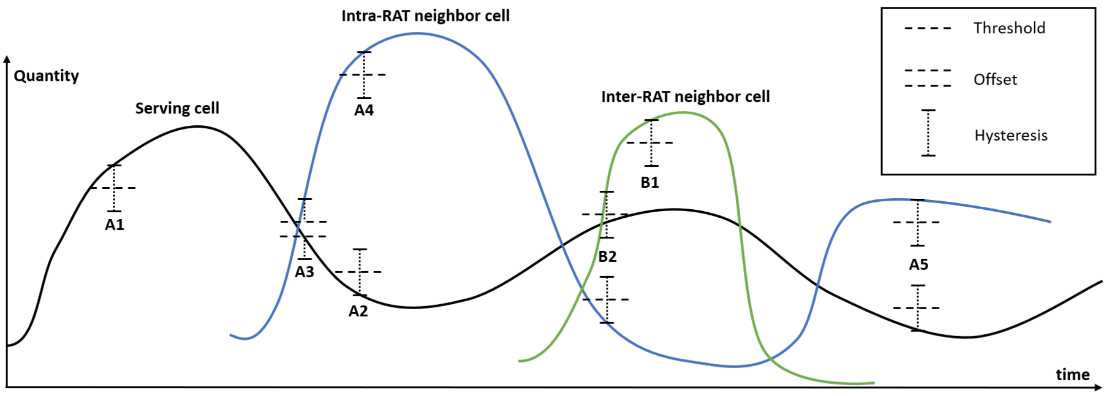

FIGURE 2.2: LTE mobility events.

data according to a schedule established by the Element Manager (EM). This aspect of the management environment is named Performance Management. The purpose of any PM activity is to collect data, which can be used to verify the physical, virtual and logical configuration of the network and to locate potential problems as early as possible. Collected performance data is aggregated into counters which may be classified into different families. In E-UTRAN, main families of counters are the following:

- DRB. Measurements related to Data Radio Bearer (DRB).
- RRC. Measurements related to Radio Resource Control.
- RRU. Measurements related to Radio Resource Utilization.
- ERAB. Measurements related to E-UTRAN Radio Access Bearer (E-RAB).
- HO. Measurements related to Handover.
- S1SIG. Measurements related to S1 Signaling.
- SRB. Measurements related to Signaling Radio Bearer.
- PAG. Measurements related to Paging.
- EQPT. Measurements related to Equipment.
- UECNTX. Measurements related to UE context.

- TB. Measurements related to Transport Block.
- MR. Measurements related to Measurement Report.
- PEE. Measurements related to Power, Energy and Environmental (PEE) parameters.
- LWI. Measurements related to LTE and Wireless Local-Area Network (WLAN) integration, including LTE-WLAN aggregation (LWA) and LTE-WLAN integration with Internet Protocol Security (IPSec) tunnel (LWIP).
- ENDC. Measurements related to LTE-5G Dual Connectivity.

In addition, counters may have different type of collection methods [40]:

- Cumulative Counter. The network element maintains a running count of the event being counted during the recording period.
- Status Inspection. Network elements maintain internal counts for resource management purposes during the recording period.
- Gauge. A Gauge measurement increases or decreases depending on the activity in the system. It is used when the measured data varies during the measurement period. Gauge contains the next four parameters:
  - Average. Averaged value during the recording period.
  - Minimum. Minimum value during the recording period.
  - Maximum. Maximum value during the recording period.
  - Last update. Last value recorded.
- Discrete Event Registration. Data related to a particular event is captured every n (n can be 1 or higher) occurrences of the event.

Moreover, E-UTRAN counters can be aggregated at different levels. The most frequently used levels are:

- Network. Counter value represents the status of the entire network.

- eNodeB. Information is collected per eNodeB.
- Cell. Information is collected per cell.
- Relation. This level is used for mobility statistics. Counters at this level will represent information related to handover source and target cell pairs.

PM counters can be combined to create high level indicators representing the end-user perception of the performance of the network. These indicators are known as Key Performance Indicators. KPIs are typically used by operators in order to benchmark networks against each other and to detect problematic areas. The main groups in which KPIs are divided into are:

- Accessibility. In this group, KPIs related to E-RAB setup, initial context setup procedure, S1 signaling and RRC connection are included.

  An example of KPI in this group is *Initial E-RAB Establishment Success Rate*, which can be calculated as:

  $$\begin{gathered}\text{Initial E-RAB ESR (\%)} = \\ 100 \times \text{RRCESTABR} \times \text{S1SIGCONNESTABR} \times \text{ERABESTABINITR}\end{gathered} \tag{2.1}$$

  where

  $$\begin{gathered}\text{RRCMMEOVL} = \\ \text{RrcConnEstabFailMmeOvlMos} + \text{RrcConnEstabFailMmeOvlMod}\end{gathered} \tag{2.2}$$

  and

  $$\begin{gathered}\text{S1SIGCONNESTABR} = \\ \frac{\text{S1SigConnEstabSucc}}{\text{S1SigConnEstabAtt} - \text{S1SigConnEstabFailMmeOvlMos}}\end{gathered} \tag{2.3}$$

  and

  $$\text{ERABESTABINITR} = \frac{\text{ErabEstabSuccInit}}{\text{ErabEstabAttInit}} \tag{2.4}$$

  being:

  - RrcConnEstabSucc. The total number of successful RRC Connection Establishments.
  - RrcConnEstabAtt. The total number of RRC Connection Request attempts.

  - RrcConnEstabAttReatt. The total number of RRC Connection Request attempts that are considered as re-attempts.
  - RrcConnEstabFailMmeOvlMos. The total number of failed RRC Connection Establishments with establishment cause Mobile Originating Signaling due to MME overload.
  - RrcConnEstabFailMmeOvlMod. The total number of failed RRC Connection Establishments with establishment cause Mobile Originating Data due to MME overload.
  - S1SigConnEstabSucc. The total number of successful S1 signaling connection establishments.
  - S1SigConnEstabAtt. The total number of S1 Signaling connection establishment attempts for any establishment cause.
  - S1SigConnEstabFailMmeOvlMos. The total number of failed S1 signaling connection establishments with establishment cause Mobile Originating Signaling due to MME overload.
  - ErabEstabSuccInit. The total number of successful initial E-RAB Establishments. Initial E-RABs are all E-RABs present in the S1 message Initial Context Setup Request.
  - ErabEstabAttInit. The total number of initial E-RAB setup attempts. Initial E-RABs are all E-RABs present in S1 message Initial Context Setup Request.

- Retainability. This group includes KPIs related to abnormal release of established E-RAB.

  An example of KPI in this group is *E-RAB Retainability*, defined as:

$$\text{E-RAB Retainability (\%)} = 100 \times \frac{\text{ErabRelAbnormalEnbAct} + \text{ErabRelAbnormalMmeAct}}{\text{ErabRelAbnormalEnb} + \text{ErabRelNormalEnb} + \text{ErabRelMme}} \tag{2.5}$$

  being:

  - ErabRelAbnormalEnbAct. Number of abnormal E-RAB Releases per cell initiated by the eNB. This counter is stepped if data was present in UL or DL buffers.

  - ErabRelAbnormalMmeAct. Number of abnormal E-RAB Releases per cell initiated by the MME. This counter is stepped if data was lost in either UL or DL buffers.
  - ErabRelAbnormalEnb. The total number of abnormal E-RAB Releases triggered by the eNB per cell.
  - ErabRelNormalEnb. The total number of normal E-RAB Releases triggered by the eNB per cell.
  - ErabRelMme. Number of E-RAB Releases per cell initiated by the MME excluding successful handover. This counter is stepped regardless of whether data was or was not lost in UL or DL buffers.

- Integrity. This group can be divided into three parts: latency, throughput and packet loss.

  An example of KPI in this group is *Average DL UE Latency*, defined as:

$$\text{Avg. DL UE Latency (ms)} = \frac{\text{PdcpLatTimeDl}}{\text{PdcpLatPktTransDl}} \tag{2.6}$$

  being:

  - PdcpLatTimeDl. Cummulative DL Latency for measurement period. Effective DL latency time comprises the time from Packet Data Convergence Protocol (PDCP) DRB Service Data Unit (SDU) entering buffer until the first data has been transmitted to UE.
  - PdcpLatPktTransDl. Number of DRB packets for DL latency measurements.

- Mobility. This group includes KPIs related to handover and redirections performance.

  An example of KPI in this group is *Handover Execution Success Rate*, calculated as:

$$\begin{gathered}\text{Handover Execution SR (\%)} = \\ 100 \times \frac{\text{HoExeSuccLteIntraF} + \text{HoExeSuccLteInterF} + \text{HoExeSucc}}{\text{HoExeAttLteIntraF} + \text{HoExeAttLteInterF} + \text{HoExeAtt}}\end{gathered} \tag{2.7}$$

  being:

- HoExeSuccLteIntraF. The number of successful intra LTE intra frequency handovers.
- HoExeSuccLteInterF. The number of successful outgoing intra LTE inter frequency handovers.
- HoExeSucc. The number of successful Single Radio Voice Call Continuity (SRVCC) handover executions from LTE to GSM/EDGE Radio Access Network (GERAN) plus the number of successful handovers to Universal Terrestrial Radio Access Network (UTRAN) or Time Division Synchronous Code Division Multiple Access (TD-SCDMA).
- HoExeAttLteIntraF. The number of attempted intra LTE intra frequency handovers.
- HoExeAttLteInterF. The number of attempted outgoing intra LTE inter frequency handovers.
- HoExeAtt. The number of attempted SRVCC handover executions from LTE to GERAN plus the number of attempted handovers to UTRAN or TD-SCDMA.

• Availability. This group contains KPIs related to the outage of network elements.

An example of KPI in this group is *Cell Availability*, defined as:

$$\text{Cell Availability (\%)} = 100 \times \frac{\mathrm{N} \times \mathrm{T} - \sum_{N} (\text{CellDowntimeAuto} + \text{CellDowntimeMan})}{\mathrm{N} \times \mathrm{T}} \tag{2.8}$$

being:

- N. Number of cells.
- T. Time of collection.
- CellDowntimeAuto. Time the cell has been disabled due to a fault.
- CellDowntimeMan. Time the cell has been disabled due to:
  - Administrative state of the cell has been set to locked by the operator.
  - The operator has performed a reconfiguration request on an unlocked cell which requires the cell to be taken down temporarily.

2.2 5G Overview

The progress in technology is often correlated with the demands of the society. Thus, in the same manner as 4^{th} Generation (4G) emerged as a technology focused on data transfer by enhancing data rates, 5G standard arose aiming at supporting three main application areas:

- Enhanced Mobile Broadband (eMBB). eMBB aims at providing service to a constantly increasing number of connected devices and their requirements of higher data rates.
- Ultra Reliable Low Latency Communications (URLLC). URLLC refers to providing service to latency sensitive devices and mission critical applications requiring robust communications like tele-surgery, industry automation and intelligent transportation.
- Massive Machine Type Communications (mMTC). With the advent of IoT, millions of different devices are connected to the Internet. Among these devices, some require low data rates, some need to save energy consumption, some only receive data, some only transmit data, and some require short connection periods. Therefore, mMTC refers to providing service to a large number of devices and will cope with all their heterogeneous requirements.

In order to meet the previous requirements, 5G networks introduce a series of concepts:

- Massive Multiple-Input Multiple-Output (MIMO) and beamforming. Although these concepts arose in LTE-Advanced networks, their potential is fully exploited in 5G:
    - Massive MIMO is a special case of MIMO in which antennas are composed of a large number of radiating elements. As in MIMO, massive MIMO aims at increasing the quality of the transmitted signal and the channel capacity while maintaining the spectrum utilization.

- Beamforming is the ability of an antenna to adapt its radiation pattern based on a particular scenario. This can be easily done in antennas composed of an array of radiating elements after modifying the phase of the signal transmitted by every element. Thus, radiation patterns from all the radiating elements are combined to create a single antenna with a more directive beam. The higher the number of radiating elements in the antenna, the narrower the main lobe of the beam and the lower the side lobes. 5G applies beamforming in two ways:
  - Beam steering. The direction of the main lobe of the beam is calculated dynamically to track the user position.
  - Beam switching. The antenna has a predefined number of beams pointing towards fixed directions and the user may switch between them when RF conditions require so.

- Spectrum. Based on the carrier frequencies used, the spectrum of 5G networks can be divided into three bands:
  - Low-band spectrum. These are the carriers below 1 GHz. This group offers wide coverage but is limited in terms of peak data rates.
  - Mid-band spectrum. These are the carriers between 1 GHz and 6 GHz. These, combined with Massive MIMO and beamforming, provide better data rates than low-band spectrum.
  - High-band spectrum. Also referred to as Millimeter Waves (mmWaves), these are the carriers above 6 GHz. The highest data rates and lowest latencies are offered in this band. However, since the main limitation of this band is its high propagation losses, network densification is required to provide wide coverage.

- Numerology. In 5G, the subcarrier spacing and the symbol duration is not fixed. These can be modified depending on the needs. Thus, instead of having 15 kHz of subcarrier spacing and 1 slot per subframe, several configurations are valid [41] as in Table 2.1.

- Multi-connectivity. Multi-connectivity is an extension of dual connectivity presented in LTE-Advanced [42]. This technique allows users to connect to

Table 2.1: 5G numerology.

Subcarrier spacing configuration	Subcarrier spacing (kHz)	Extended cyclic prefix	Symbols per slot	Slots per subframe
0	15	NO	14	1
1	30	NO	14	2
2	60	NO	14	4
2	60	YES	12	4
3	120	NO	14	8
4	240	NO	14	16

multiple BSs at the same time. This is useful to avoid ping-pong handovers and to increase data rates.

The deployment of 5G networks is planned to be performed in two phases:

- The first phase is known as 5G Non Standalone (5G NSA). In this phase the already deployed LTE infrastructure is used along with 5G radio interface known as New Radio (NR) (see Fig. 2.3)
- The second phase is known as 5G Standalone (5G SA). In this phase, the 5G System (5GS) will be deployed. 5GS is composed of Next Generation RAN (NG-RAN) and 5G Core Network (5GC) [43, 44]. Figure 2.4 depicts the main elements of the 5GS:
    - ng-eNB. This element is an enhanced eNodeB that connects to the 5GC but uses LTE air interface to communicate with the UE.
    - gNB. This element is the next generation nodeB. gNB is connected to the 5GC and communicates with the UE using NR air interface.
        - gNB-CU. This control unit is a logical node that includes functions like mobility control, transfer of user data, radio access network sharing, positioning or session management.
        - gNB-DU. This distributed unit is a logical node controlled by the control unit that includes a subset of functions depending on the

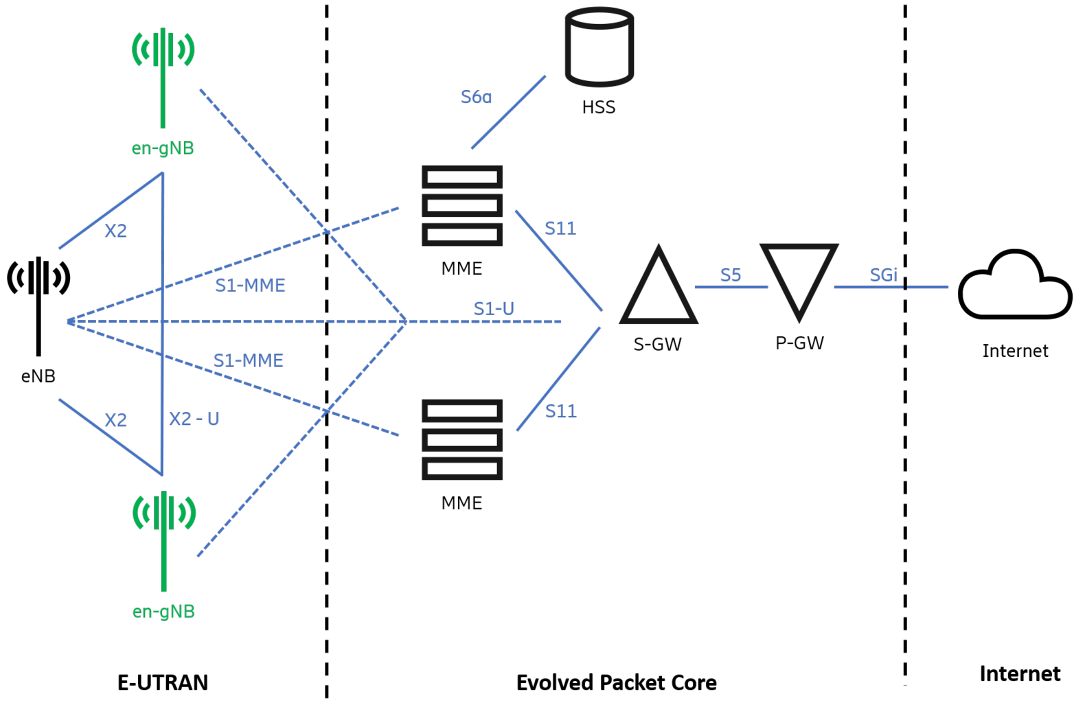

FIGURE 2.3: 5G NSA architecture.

functional split option. Functional splits specify the protocol stack layers included in this node.

- Access and Mobility Management Function (AMF). Some of its functions are termination of NAS signaling, NAS ciphering and integrity protection, registration management, connection management, reachability management, mobility management, access authentication and authorization and security context management.
- Session Management Function (SMF). Some of its functions are session management, UE IP address allocations, Dynamic Host Configuration Protocol (DHCP) functions, charging data collection and DL data notification.
- User Plane Function (UPF). Some of its functions are packet routing, packet inspections, QoS management, interconnection with Data Network and anchor for mobility.
- Policy Control function (PCF). This function provides a unified policy framework.

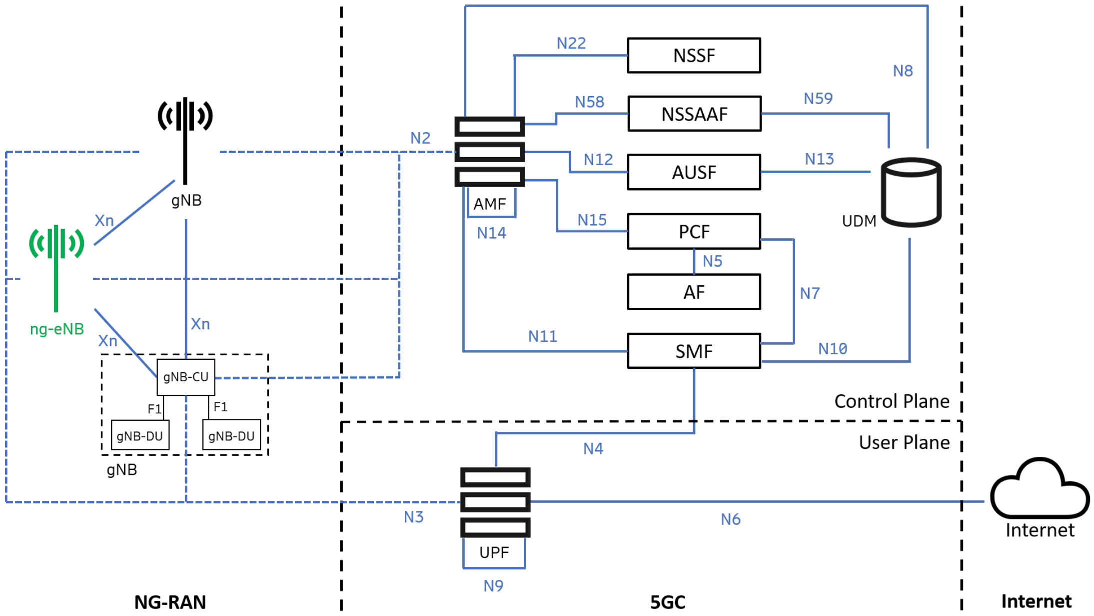

FIGURE 2.4: 5G SA architecture.

- Authentication Server Function (AUSF). This function acts as an authentication server.
- Unified Data Management (UDM). This function generates authentication and key agreement credentials, identifies users, authorizes access and manages subscriptions.
- Application Function (AF). This function supports services like application influence on traffic routing or interaction with policy framework for policy control.
- Network Slice Selection Function (NSSF). This function determines the Network Slice instances to serve the UE.
- Network Slice Specific Authentication and Authorization Function (NSSAAF). This function supports the authentication and authorization for Network Slice.

2.3 Self-Organizing Networks

Over the last years, mobile networks have evolved considerably in order to support the new services demanded by the subscribers. In order to provide higher availability, higher data rates and lower latencies while keeping high robustness, networks have increased their complexity. Consequently, SON arose as an alternative for mobile operators to overcome the CAPEX and OPEX increase by automating traditional tasks. In particular, the main objectives of SON are:

- Reduction of OPEX by decreasing human effort in design, installation, maintenance, optimization, diagnosing, and healing of the network.
- Reduction of CAPEX by efficiently using the network elements and spectrum.
- Improvement of user experience and service quality.
- Improvement of network performance by optimizing network efficiency and service quality.

Previous objectives are achieved by many different SON algorithms. These algorithms are specialized in automating specific tasks and, in order to do so, they follow the next phases:

- Collection. During this phase, network information is collected. Based on the source of the data, the information analyzed by the SON algorithms can be classified into the following types [45]:
  - CM. Information related to the configuration of network elements.
  - PM. Counters that provide information about the status of the network (e.g. number of dropped calls or number of successful handovers).
  - Alarms. Warning messages triggered when there is a failure in a network element.

  - DT. Measurements taken by field engineers using specialized equipment. These measurements provide information such as signaling messages between the network and the UE or the actual coverage and interference that the UE observes. In addition, measurements are positioned by geo-location equipment like Global Positioning System (GPS), Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS) or Galileo so that map fingerprint can be obtained.
  - MT [26]. Signaling messages between network and UEs. Unlike DT, mobile traces are automatically collected by the network. With MDT [27, 28, 29, 30], geo-location information is also reported by the positioning systems of the UEs.
  - Context information. Environment-related information (e.g. weather, geographical conditions, type of area or UE distribution).
  - KPI. Meaningful statistics calculated combining the previous sources of data (e.g. handover success rate, defined as the ratio between the number of successful handovers and the total number of handovers).

- Analysis. The current status of the network is identified in this phase.
- Execution. In this phase, the main functionality of the algorithm is executed, and the required action is determined.
- Implementation. This final phase implements the actions proposed during the execution phase.

Additionally, the architecture of SON functions can be classified into three groups depending on the network element in which the SON algorithms are executed: distributed, centralized and hybrid. In distributed SON architectures, the algorithms are run at the network nodes and they only have access to the data collected in the network node. In these architectures, execution time is short, and nodes may exchange their related messages directly with each other. In centralized SON architectures, the algorithms are run at the network management level and they have access to data from all network elements. Therefore, although centralized SON architectures have a longer execution time than in distributed SON

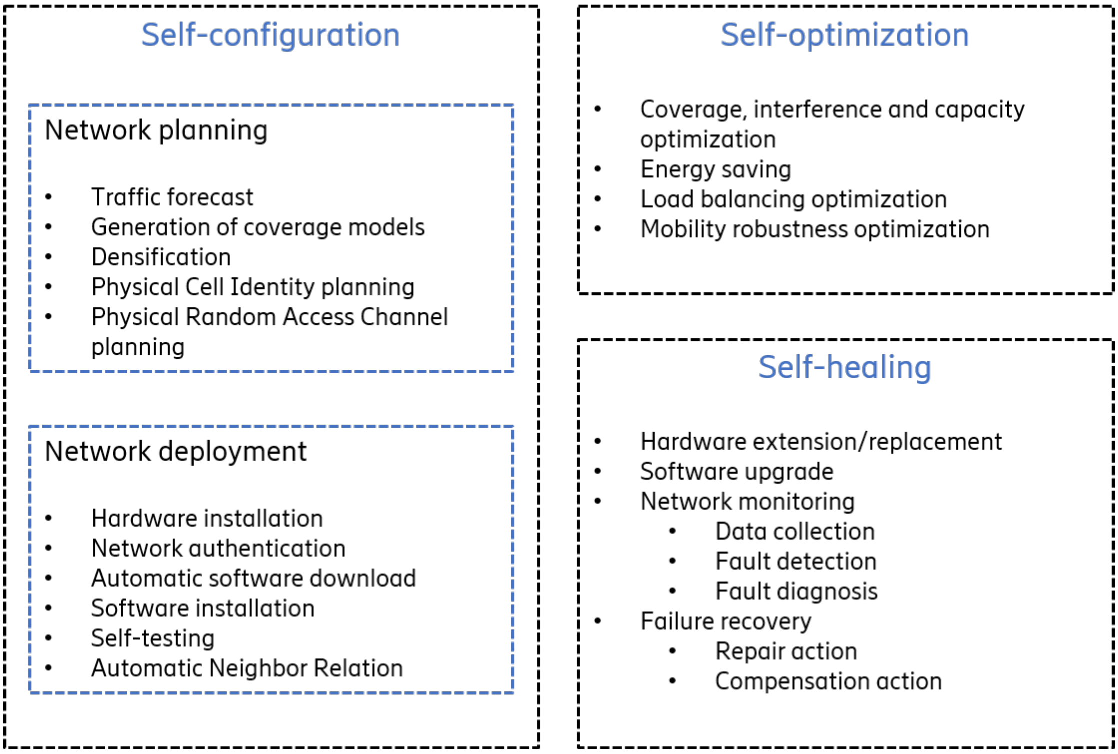

FIGURE 2.5: SON categories.

architectures, centralized SON architectures are suitable for orchestrating the behavior of radio network equipment across an entire network of multi-vendor and multi-technology environments. Finally, the hybrid SON architecture is characterized by having part of the SON algorithm in the network management level and part in the network elements.

As depicted in Fig. 2.5, SON functions can be categorized into three main groups [4, 19]: self-configuration [12], self-optimization [12] and self-healing [16].

2.3.1 Self-configuration

Self-configuration is concerned with two different aspects: network planning and network deployment. Network planning consists in the design of new elements to be added to the network. Network deployment involves the installation and periodical updating of new network elements. The main tasks of self-configuration systems are:

- Network planning:
  - Traffic forecast. Prediction of future demanded traffic based on current traffic patterns.
  - Generation of coverage models. Based on theoretical models and/or field measurements, full coverage fingerprints are generated.
  - Densification. Based on coverage and/or capacity needs, locations where to deploy new BSs are identified.
  - PCI planning. PCI is a cell identifier used during access and handover procedures. Since the number of PCIs is limited, ensuring that adjacent cells do not present the same PCI is crucial to avoid conflicts that would lead to access or handover failures.
  - Physical Random Access Channel (PRACH) planning. PRACH channel is used for initial network access or when UE performs handover procedures. The random access procedure begins with the eNodeB broadcasting a list of predefined Zadoff-Chu [46] sequences. The UE randomly selects one of these sequences to send a random access request via the PRACH. As for PCIs, a proper planning of these sequences is required in order to avoid conflicts that would lead to access or handover failures.
- Network deployment:
  - Hardware installation. Initial configuration of network elements.
  - Network authentication. The network element is identified by the EM and the authentication process is executed.
  - Automatic software download. The EM or network elements themselves trigger the download of new software packages.
  - Software installation. Network elements download parameter settings in order to configure transport and radio functionalities.
  - Self-testing. Correct operation of network elements is checked.
  - Automatic Neighbor Relation (ANR). Neighbor cell relations are created and deleted by network elements through the Neighbor Relation Table. These relations are updated based on UE RF measurements.

2.3.2 Self-optimization

Self-optimization is the functionality of SON focused on the automatic configuration of system parameters in order to adapt the network to the constant changes of the RF environment. Some changes in the RF environment could be the construction of new infrastructures that either act as RF obstacles (e.g. buildings, bridges, etc.) or generate RF interference (e.g. electric power plants, frequency inhibitors, etc.), changes in the traffic patterns of subscribers due to the construction of buildings (e.g. a new mall) or seasonal effects (e.g. in summer more subscribers are expected at coastal areas). Therefore, the network needs to be automatically adjusted to keep its efficiency to best standards. Among the functions of self-optimization systems, the following can be found:

- Coverage, interference and capacity optimization. This function aims at configuring network parameters such as the azimuth of the antennas, their mechanical tilts, electrical tilts or their transmission power in order to maximize the network serving area, minimize inter-cell interference and guarantee that capacity requirements are satisfied.
- Energy saving. Operators try to reduce the energy consumption of their networks since this affects their OPEX. Therefore, self-optimization has a function that aims at reducing the power consumption of network elements by shutting these down when they are not essential to keep network performance requirements.
- Load balancing optimization. This function modifies mobility parameters in order to redirect traffic from congested cells to neighboring cells with enough available resources to provide service to subscribers.
- Mobility robustness optimization. This function detects problems in mobility procedures and finds configurations of mobility parameters that fix these problems. Among these problems, the main three are: too late handover (i.e., the handover was triggered when signal level was too low to keep the communication between the UE and the source cell), too early handover (i.e., the handover was triggered when signal level was too low to keep the

communication between the UE and the target cell) and handover to wrong cell (i.e., a better cell should have been chosen as the target cell of the handover procedure).

2.3.3 Self-healing

Self-healing function of SON aims at finding faults in network elements that are negatively affecting the network performance. Self-healing covers the following functions [3]:

- Hardware extension/replacement. This function aims at replacing faulty hardware of a network element or extend it to increase the network capacity, requiring minimal intervention.
- Software upgrade. As done in self-configuration, self-healing may trigger the automatic download and installation of new software that fixes or minimizes network failures.
- Network monitoring. This function uses sources of data of the network with the goal of detecting network faults and diagnosing their root causes. This function is divided into the next phases:
  - Data collection. During this phase, network data such as CM, PM, MT, alarms and KPIs is collected.
  - Fault detection. During this phase, cells having bad performance are identified. For this purpose, the automatic detection system uses different techniques such as establishing thresholds in performance indicators to guarantee a minimum quality or creating patterns based on normal network performance to be used as reference.
  - Fault diagnosis. In case the detection system has found a problem, this phase tries to identify the root cause of it by inspecting network data.
- Failure recovery. This function is executed when faults are identified by the network monitoring function. This function implements the required recovery actions to solve or compensate the problem:

- Repair action. According to the fault identified, this function determines the proper actions to solve the problem. These actions are either executed remotely (e.g., modification of network parameters or reboot of network elements) or locally (e.g. equipment replacement).
- Compensation action. This action does not aim at solving the root cause of the problem but to reduce its negative effects on the network performance by reconfiguring the affected cell and cells adjacent to it. Generally, this action is executed in parallel with repair action until the problem is solved.

2.4 State of the art of main challenges

In this section the state of the art of the challenges identified in this thesis will be presented. These challenges are, the enhancement of design methods to support the design of 5G FWA networks, the cost-efficient calibration of predicted RF propagation models and the automatic detection of swapped sectors.

2.4.1 Design methodology for 5G FWA networks

Methods to design FWA networks try to find the location of BSs and CPEs antennas (referred as network planning) as well as the network parameter configuration (referred as network configuration) that results into the optimal network performance. This can be considered as a combinatorial problem in which all possible locations of BSs and CPEs antennas as well as network parameter values must be considered.

Initially, the exercise of designing mobile networks was done by network experts who, based on their experience and skills, evaluated different network configurations to find the best performing one. However, with the growth of mobile networks, this task became unfeasible and automatic methods, known as Automatic Cell Planning [32] arose. These methods use metaheuristic algorithms to find either local or global optimal configurations of network parameters and locations of network elements [10]. In order to do so, metaheuristic algorithms try to minimize the value of a cost function that depends on the objectives to achieve. Specifically, ACP methods define cost functions based on the network performance requirements established by the operator. Generally, these requirements are:

- Good coverage. Coverage is used to guarantee that connections can be established. For this, a threshold indicates the minimum received signal strength determined by the operator.
- Good dominance. Dominance is used to identify how cells in the network interfere to each other. Specially, how the best server (i.e., the cell received with highest signal strength) is interfered by others. Since network performance is usually limited by interference, dominance is useful to estimate the QoS. Dominance has two components:
  - Minimum received signal strength of a cell to be considered as interfering the serving cell.
  - Maximum number of cells interfering the best server.
- Good capacity. Capacity is used to identify cells that are potentially serving more subscribers than its available resources. Determined by a peak data rate value supported by a cell.

The performance requirements defined by the operator are then evaluated in all locations where subscribers could be found. In order to do so, ACP methods divide the area of the network into a discrete set of locations small enough so that RF propagation effects can be considered as invariant in the whole discrete area. Thus, cost function is defined as the contribution of all these discrete locations to the network performance requirements established by the operator.

Furthermore, the operator may add weights to these contributions. Some of these weights are the traffic expected to be served on a discrete location (so that locations with higher traffic are more significant), the relative importance of a performance requirement over a different one (e.g., having good coverage could be preferred over having good dominance) or the cost of a network parameter change (e.g., change the transmission power of an antenna could have an associated cost lower than modifying an azimuth value).

Therefore, a typical cost function is described as next:

$$\Phi(\mathbf{S}) = \sum_{i=1}^{N} \alpha_i \sum_{j=1}^{M} \omega_j \delta_{ij}(\mathbf{S}) \tag{2.9}$$

$$\delta(\mathbf{S}) = \begin{cases} 0 & \text{if performance requirement is achieved} \\ 1 & \text{otherwise} \end{cases} \tag{2.10}$$

where N is the number of discrete locations in the network and M is the number of performance requirements (i.e., coverage, dominance, capacity, etc.). The traffic in discrete location i is represented as α_i. The relevance of performance requirement j is indicated by weight ω_j. $\delta_{ij}(\mathbf{S})$ is the value of function $\delta(\mathbf{S})$ for performance requirement j at discrete location i.

Finally, in order to evaluate the cost function, ACP methods make use of signal level maps. These maps may be obtained in several ways: using theoretical models, extrapolating empirical models, performing drive tests, collecting network mobile traces, etc. Having these maps and the radiation patterns of the transmission antennas, ACP methods recalculate the signal level of each cell in every discrete location after a network parameter has been changed so that the cost function is reevaluated.

However, ACP methodology has two main problems that need to be addressed:

1. ACP algorithms were designed to plan and configure networks in which the subscribers can freely move anywhere. However, in the case of FWA networks, subscribers are located at their homes and no mobility is considered. In fact, the location of a subscriber is determined by the static position of the CPE antenna. Therefore, traffic is not spread all over the service area of

the network cells, but it is concentrated in the locations where the antennas of the CPEs are installed.

2. Current ACP algorithms execute network planning and network configuration sequentially. This is, these algorithms firstly find the optimal locations of network elements and, once all locations are found, the optimal configuration of network parameters is determined.

These two problems will be addressed in this thesis.

2.4.2 Cost efficient calibration of RF propagation models

During network optimization activities, RF propagation maps are used. Frequently, these maps are rasterized so that the area covered by the mobile communication network is discretized in small bins. Each of these bins contains signal levels received from different cells in the network. Based on these maps, optimization algorithms are able to recalculate the changes that received signal levels would experience after applying modifications in network parameters.

Traditionally, operators used either theoretical or empirical models to generate RF propagation maps. However, these models were not accurate enough, so operators started to carry out DT activities in order to collect real signal measurements from live networks to build these maps. However, these activities are expensive both in CAPEX and OPEX and operators started to use a hybrid solution that combines both theoretical models and live network data.

This solution consists of building RF propagation maps from theoretical models that later are recalibrated using data from MT. Specifically, operators configure their networks so that UE is commanded to report RF measurements periodically. Thus, using these measurements, operators generate signal distributions per cell and signal to interferer distributions per pair of cells. Both these distributions are discretized into bins so that the number of samples reported by UE that falls into a bin is aggregated. Then, operators also build signal distributions per cell and signal to interferer distributions per pair of cells from their RF propagation maps generated from theoretical models. Thus, the distributions extracted from theoretical models are calibrated using the distributions extracted from network measurements. Having the theoretical distributions already calibrated, operators transform them into RF propagation maps that fit the measurements collected from the network.

This hybrid approach is extensively used by operators and has provided good results in optimization activities. However, accessibility to MT is not always feasible. The reason behind this is that either vendors do not provide interfaces to access these data or that the accessibility has associated license costs. Moreover, building distributions from network measurements requires high computational cost and, commanding UE to report measurements periodically might both overload UL control channels and drain the batteries of the devices.

Therefore, this thesis will propose a universal methodology capable of generating the distributions required in order to calibrate RF propagation maps from theoretical models in LTE and 5G networks.

2.4.3 Automatic detection of swapped sectors

Conventionally, DT activities are used by operators in order to detect swapped sectors. In these activities, field engineers perform RF measurements at different network locations in order to build maps with received signal level from network cells. Thus, using these maps, the main directions at which antennas are pointing can be determined as the directions at which their corresponding signal levels are higher.

However, DT activities involve high CAPEX and OPEX. Additionally, correcting swapped sectors by using DT generally implies multiple site visits: DT for detection, issue correction and final DT for verification.

In order to avoid the necessity of performing DT to identify swapped sectors, both vendors and operators researched new techniques. One of these techniques is based on interference measurements reported by UE and available in MT [47]. However, this method requires high computational capability in order to decode and process signaling messages. In addition, this method is not enough accurate as it relies on RF measurements which are prone to present high variability. A second technique [48] involves a system capable of detecting swapped sectors using network mobility statistics. The main advantage of this solution is the low computational capability required, since network statistics are standardized [39]. However, this method presents a high rate of false positives detection when true positives detection rate is acceptable.

This thesis will propose several automatic methods that improve results obtained by state-of-the-art techniques designed to detect swapped sectors.

Chapter 3

Research outline

This chapter is divided into two sections. The first section presents a description of the research publications derived from this thesis, their relationship with the main objectives to accomplish and their contributions to the state of the art. Particularly, these publications are divided into three groups: self-configuration, self-optimization and self-healing. The second section of this chapter explains the research methodology followed in this thesis. This includes all techniques, equipment and tools that have been used.

3.1 Description of the outcomes

In this section, all outcomes derived from this thesis are presented. All these outcomes address the objectives presented in Chapter 1. Fig. 3.1 summarizes the relationship between outcomes and objectives, so that their connection in this document is depicted. Specifically, outcomes are depicted as blocks in this figure, where for each one, the accomplished objectives and their connection with the challenges of this thesis is presented.

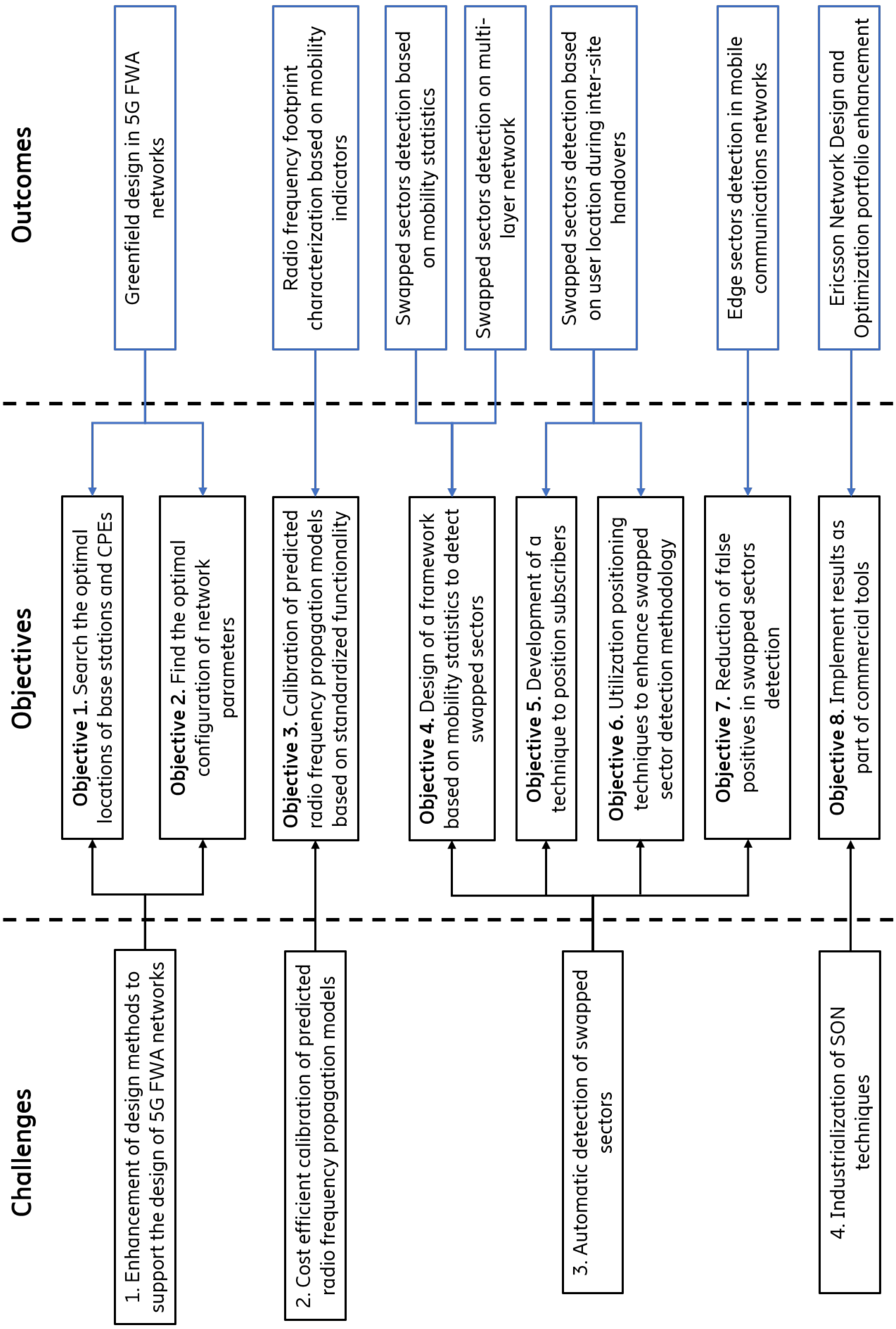

Figure 3.1: Challenges, objectives and outcomes.

3.1.1 Greenfield design in 5G FWA networks [I] (Chapter 4)

As previously presented, Chapter 4 corresponds to self-configuration concept of SON. Therefore, this publication aims at solving the main objectives of this thesis related to self-configuration. This is, this publication aims at finding both the best locations where to deploy network BSs and the best locations where to install the antennas of CPE (Objective 1) as well as finding the best configuration of network parameters (Objective 2).

In order to achieve this, this publication proposes a new optimization cost function applicable to FWA greenfield design activities which, unlike other state-of-the-art cost functions, considers that the location of the CPE antenna will be the best among all the candidate locations in a household. Therefore, any other location in the household will not contribute to the cost function. This novel cost function allows to reach a better solution by ignoring locations that will not affect the final performance of the network. Additionally, this publication also proposes an iterative algorithm that combines optimization functions extracted from self-optimization with network planning so that final BS locations are determined considering that the current state of the network is the best state possible. This is, firstly a new BS is added to the network (network planning) and secondly, the network configuration is optimized (network configuration) before adding a new BS.

This algorithm results in a network design that requires a lower number of BSs than when network planning and network configuration stages are executed independently to achieve the desired performance of the network. For this purpose, this publication utilizes several inputs: Candidate locations where to deploy network BSs, pathloss figures from candidate BS locations to CPE locations, antennas transmission power and antennas radiation patterns, among others.

The methodology proposed in this publication was evaluated using data from a real suburban environment and the results obtained demonstrated that the final network performance was improved with respect to state-of-the-art methods while the deployment costs (i.e., the number of required network BSs) were reduced.

3.1.2 Radio frequency footprint characterization based on mobility indicators [II] (Chapter 5)

This publication is placed in the context of self-optimization concept of SON. Specifically, this publication proposes a methodology to calibrate RF propagation models based on predictions using standardized functionalities available in commercial LTE and 5G networks (Objective 3). In order to do so, this publication presents a methodology that, using the configuration of network parameters and network performance statistics, is capable of generating coverage and interference distributions. Particularly, this method proposes the correlation of the thresholds of mobility events involved in mobility procedures with the number of connections and handovers performed. Therefore, the execution of DT activities is avoided.

The methodology proposed in this publication was evaluated using data from a commercial LTE network, proving it as a universal technique to characterize the RF footprint.

3.1.3 Swapped sectors detection based on mobility statistics [III] (Chapter 6.1)

This publication, like all publications in Chapter 6, aims at contributing to the state of the art of self-healing techniques. Particularly, this publication addresses the objective of designing a framework to detect swapped sectors in mobile communication networks (Objective 4). In order to do so, this publication proposes and compares two different novel methodologies. Both methodologies use as input the location of the BSs in the network, the expected azimuths of the sectors as well as mobility statistics such as handover attempts.

The first methodology (referred as Method I) proposes to identify a range of angles (referred as solid angle) per sector into which handovers of the sector are expected to be attempted according to the azimuth of the sector. Then, a cost function that combines the number of handovers and the distance at which the handovers are performed is presented. For this purpose, the distance between source and target cells in the handover procedure is used. This cost function is calculated for every sector with respect to all solid angles of co-sited sectors. This is, in a site divided into three sectors, the cost function is evaluated nine times (three sectors multiplied by three different solid angles in the site). Finally, if the cost function that results the greatest value for a sector is not the one corresponding to its solid angle, the sector is identified as a candidate to be swapped. Specifically, if the cost function that obtains the greatest value for a given sector is the one corresponding to the solid angle of a different one and that different one has its greatest cost function corresponding to the solid angle of the first sector (this is referred as reciprocity criterion), both sectors are considered as swapped. This reciprocity criterion is also extended to rotated trios.

The second methodology (referred as Method II) proposed in this publication presents a set of equations in order to calculate the actual azimuth towards which a sector is pointing. These equations are also based on the number of handover attempts performed from a source cell to a target cell and the distance between them. As in the first method, this second method also has associated a reciprocity criterion that allows it to identify both pairs and trios of swapped sectors. In this case, the reciprocity criterion consists in finding sectors whose computed azimuth is closer to the expected azimuth of a co-sited sector and vice-versa.

Finally, a significant number of simulations was performed where, Method I presented the lowest number of false positives whereas Method II achieved the best true positives detection rate. In addition, both methods were tested in real LTE mobile communication networks showing results aligned with the simulations performed previously. Therefore, the proposed methodologies resulted the best alternatives to DT activities.

3.1.4 Swapped sectors detection on multi-layer networks [IV] (Chapter 6.2)

As the previous publication, this publication aims at accomplishing the objective of designing a framework to detect swapped sectors in mobile communication networks (Objective 4). The main difference with the previous publication is that this method is only applicable to multi-layer networks. This publication proposes a methodology capable of detecting swapped sectors using intra-site mobility statistics between cells belonging to different frequency layers of the network.

The method presented in this publication relies on the premise that handovers from a cell in a given frequency layer towards co-sited cells belonging to a different frequency layer are more likely to be performed towards the co-sited cell in the different frequency layer of which azimuth is more similar to the one of the source cell. This publication also presents a reciprocity criterion in order to identify swapped pairs and rotated trios based on this method.

Finally, the results of this method were compared with the results of the methods proposed in the previous publication demonstrating that the true positives rate is improved while the false positives rate remains similar.

3.1.5 Swapped sectors detection based on user location during inter-site handovers [V] (Chapter 6.3)

This publication also belongs to the group of self-healing techniques and, specially, to the detection of swapped sectors in mobile communication networks. However, this publication also aims at designing a UE location technique based on standardized functionality available by default in commercial networks (Objective 5). For this, information extracted from signaling messages sent between the network and the UE is used. In particular, Timing Advance (TA) and Measurement Report (MR) messages are used. TA is the procedure used by the network to command the UE to transmit data in advance, so they arrive at the BS at their corresponding timeslot. These TA messages can be translated into distances by using the speed of electromagnetic fields in a given medium. MR messages are sent from the UE to the network in order to notify that RF conditions have been modified in a manner that mobility procedures could be triggered. These MR messages include the cells that have been measured and the signal levels of these. Therefore, when a handover procedure has been initiated by the network due to RF conditions, at least one MR message was sent previously by the UE. This publication proposes a UE location technique that utilizes TA messages sent before and after the handover procedure so that the distance between the UE and the source and target cells of the handover can be calculated. These two distances can be represented as circumferences surrounding the BSs to which source and target cells belong. Therefore, when source and target cells belong to different BSs, these two circumferences intersect in two different points. Thus, as the UE could be located in any of these two points, MR messages can be used to decide which of these two points is the actual UE location. For this purpose, the intersection point closer to the geometric center calculated from all cells available in the MR message is selected as the actual UE location.

The accuracy of this technique has been evaluated and compared with other state-of-the-art techniques using data from a commercial LTE network, demonstrating that the proposed technique provides the best results.

In addition, this publication proposes to combine this positioning technique with swapped sectors detection methods presented in previous publications in order to improve their success rate (Objective 6). Specifically, the location of the UE is used as the location of the handover procedure, instead of using the location of the target cell for this purpose. This combined method has been evaluated and has demonstrated to achieve better results than state-of-the-art methodologies in terms of both true and false positives.

3.1.6 Edge sectors detection in mobile communication networks [VI] (Chapter 6.4)

Like all publications in Chapter 6, this publication is related to self-healing techniques. Particularly, this publication arises from the need of reducing the number of false positives cases resulted from swapped sectors detection methods (Objective 7).

The different methodologies proposed by publications related to swapped sectors detection may be susceptible to identify as swapped sectors those which are not actually swapped but, due to their location in edge areas of the network (e.g., covering big lakes, seas or mountains), could cause automatic detection algorithms to fail. Therefore, identifying sectors belonging to edge areas of the network is useful in order to apply confidence criteria to the results of swapped sectors detection techniques.

Thus, this publication aims at detecting sectors that belong to network boundaries. In order to do so, three different phases are proposed. The first phase is designed to identify unconnected areas of the network so that the problem of finding edge sectors is reduced. For this, clustering algorithms are evaluated. The second phase presents a parameterizable algorithm designed to find the nodes that shape the contours of the areas identified after phase one. Finally, the last phase detects which sectors that belong to the contour nodes are pointing outside the network and can be considered as edge sectors of the network.

The solution proposed by this publication can be extended to all kind of problems in which the detection of BSs or sectors located at the boundaries of mobile communication networks could be helpful. Therefore, simulations were performed to evaluate the goodness of the proposed methodology as a detector of cells that are the worst contributors to accuracy in geolocation techniques. The results obtained proved the validity of the proposed method.

3.1.7 Ericsson Network Design and Optimization portfolio enhancement

All publications presented previously have been integrated as part of Ericsson Network Design and Optimization portfolio, which provides solutions to help operators on automating the management of their networks.

Specifically, the techniques described in publications of Chapter 4 and Chapter 5 have been implemented in *Ericsson Cell and Frequency Optimizer* tool and those methods described by publications of Chapter 6 have been implemented in *Ericsson RAN Analyzer* tool and *Ericsson Cognitive Software* platform.

Therefore, the techniques, methods and algorithms developed in this thesis are being used by the industry in order provide solutions to actual problems in commercial mobile communications networks and, at the same time, thanks to the automation of services they allow operators to reduce their operational costs.

3.2 Research methodology

The elaboration of this thesis has been divided into a set of organized stages. These phases start from knowledge augmentation in order to create a fundamental that allows the generation of beyond the state-of-the-art contributions which finally, will be disseminated. Specifically, this research methodology is divided into the following stages (see Fig. 3.2):

- Background review. One of the main aims of this thesis was to propose solutions to real problems, which could be efficiently deployed in live networks. Since this thesis has been elaborated in collaboration with Ericsson Network Design and Optimization group, actual challenges of design and optimization exercises and their current solutions were identified. Once these challenges were identified, the state of the art related to SON methodologies was revised in order to find techniques applicable to these.
- Problem formulation. As a second stage of this thesis, a set of objectives were established in order to solve the challenges previously identified. Therefore, the subjects that must be addressed and those suitable approaches to solve them were defined. One main requirement was that the proposed solution was simple and easily deployable in current networks without modifying current network equipment.
- Execution. In this stage, different techniques and methodologies were designed in order to accomplish the objectives previously specified.
- Data preparation. The fourth stage of this thesis consists in the data gathering. This thesis encompasses varied objectives which aim at solving different problems through distinct approaches. For this reason, the inputs required by the proposed methodologies could vary depending on the use case. One of the main difficulties in this thesis was the need to obtain and process data

from real networks. All data extracted from sources of data will be collected in a centralized database which will provide the different solutions proposed in this thesis with the inputs required to be assessed. The sources of data used during the evaluation of this thesis are:

- OSS. This source of data extracts raw data from commercial LTE networks to be provided to the solutions proposed in this thesis. Specifically, the data extracted for this thesis is composed of CM, PM and MT. CM data comprises information like the location of network elements, azimuth configurations, antenna beamwidths, mechanical and electrical tilt configurations of antennas, transmission power configurations, handover thresholds, handover hysteresis and E-UTRA Absolute Radio Frequency Channel Number (EARFCN). Regarding PM data, counters such as number of calls and handover procedures initiated in a cell and number of handover procedures initiated in a cell towards a given target cell have been extracted from the OSS. With respect to MT, Timing Advance and Measurement Report messages interchanged between the network and the UE have been collected. All these data have been processed using official Ericsson tools in order to feed the centralized database implemented for this thesis.
- Simulator. There are scenarios in which the required data is either not available in the OSS or a controlled system is essential. In these scenarios, simulations have been used. Particularly, a dynamic-system level simulator [49] developed in MATLAB has been used in this thesis in order to facilitate the analysis and evaluation of the proposed solutions. This simulator models a macro-cellular environment, where the number of cells and their position are configurable. In the initial phase, the main configuration parameters are initialized, propagation losses are calculated, and mobile users are generated. Subsequently, during each simulation step, the new positions of the users are calculated, and the radio resources utilization is updated. In addition, key performance indicators are updated after a configurable group of simulation steps is executed.

- Antenna radiation patterns. This source of data consists of a set of files that describe the main characteristics of the antennas, such as radiation patterns, gains and frequency ranges.
- DT. This source of data consists of a set of files that contains signal measurements performed during DT campaigns.
- Predictions. This source of data consists of files that contains the predicted coverage footprint of the different cells which comprise the network.

- Evaluation. This stage is composed of four different phases:
  - Theoretical analysis. In this phase, the equations and algorithms that describe the proposed solutions were analyzed in order to assess their validity.
  - Simulations. Simulation tools coded in Python were used in order to validate the proposed solutions before implementing them in field trials.
  - Commercial network trials. The proposed solutions were tested in commercial networks. In this way, the proposed solutions were demonstrated to be valid not only from a theoretical perspective, but they were also proved to be valid in real deployments.
  - State of the art comparison. In addition to theoretical analysis and commercial network trials, the solutions proposed in this thesis were also benchmarked against state-of-the-art solutions so that their enhancement is proved.
- Knowledge dissemination. Finally, the most relevant results of this thesis have been published in high impact journals, international conferences and national conferences. Additionally, all these solutions have been implemented as part of Ericsson Network Design and Optimization commercial tools such as *Ericsson RAN Analyzer*, *Ericsson Cell and Frequency Optimizer* and *Ericsson Cognitive Software*.

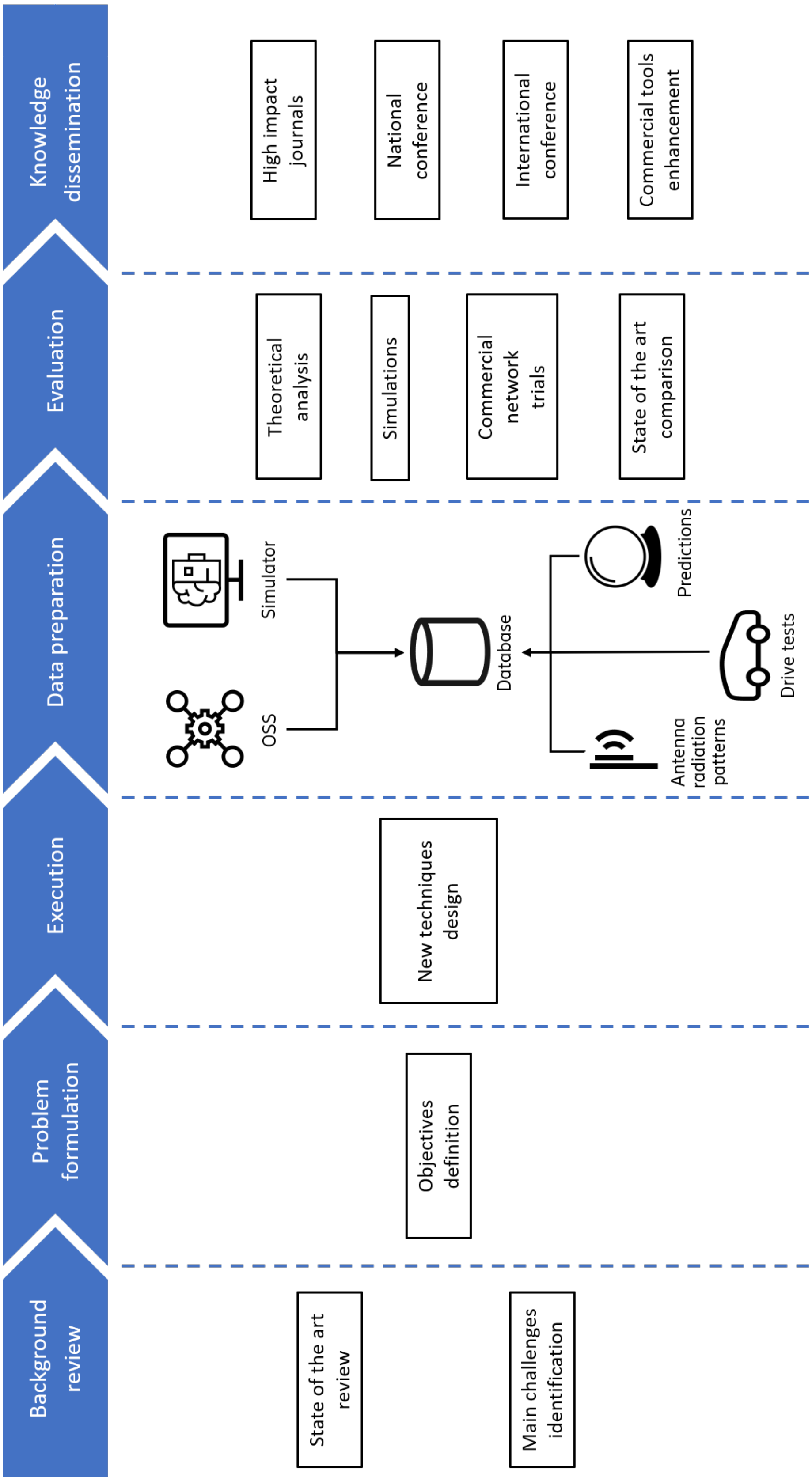

FIGURE 3.2: Research methodology.

Chapter 4

Self-planning in 5G Fixed Wireless Access Networks

4.1 Greenfield Design in 5G FWA Networks

[50] O. Kaddoura et al., "Greenfield Design in 5G FWA Networks," in IEEE Communications Letters, vol. 23, no. 12, pp. 2422-2426, Dec. 2019.
DOI: 10.1109/LCOMM.2019.2939470.

Abstract: With the arrival of 5G, Fixed Wireless Access, which aims at providing households with broadband internet access using mobile technology, has become a relevant use case. Current greenfield design techniques are not optimal since they target at optimizing the radiofrequency configuration for the whole household, sometimes at the expense of other households. However, optimizing only the spot where to install the antenna of the customer premises equipment is enough for Fixed Wireless Access networks. This letter presents an enhancement of automatic greenfield design methodology so that, apart from finding the location where to deploy network base stations and the optimal configuration of network parameters, the optimal location where to deploy customer premises equipment is also determined. A greenfield design exercise has been carried out in a real scenario proving that the proposed method both improves the final network performance and reduces the required deployment economic costs compared with state-of-the-art methodology.

Chapter 5

Radio frequency footprint characterization for self-optimization

5.1 Radio Frequency Footprint Characterization Based on Mobility Indicators

[51] O. Kaddoura, J. Outes-Carnero, J. J. Sánchez-Sánchez and R. Barco, "Radio Frequency Footprint Characterization Based on Mobility Indicators," in IEEE Wireless Communications Letters, vol. 10, no. 1, pp. 141-145, Jan. 2021.
DOI: 10.1109/LWC.2020.3023283.

Abstract: Building accurate radio frequency footprint models is an exercise often conducted to optimize the performance of mobile communication networks. Despite the large number of theoretical models, operators frequently utilize empirical radio frequency measurements taken through drive test activities. However, obtaining these measurements is an expensive activity which also, due to its discretized nature, does not cover the entire area of the network and generally produces incomplete radio frequency footprint models. A method to characterize the radio frequency footprint using network configuration and performance measurements automatically collected by the network is presented in this letter. Data from an operating commercial Long Term Evolution network has been used to validate the results of the proposed method.

Chapter 6

Swapped sectors detection as a self-healing concept

6.1 Swapped Sectors Detection Based on Mobility Statistics

[52] O. Kaddoura, R. Barco, I. Serrano and J. J. Sánchez-Sánchez, "Swapped Sectors Detection Based on Mobility Statistics," in IEEE Communications Letters, vol. 22, no. 5, pp. 1038-1041, May 2018.
DOI: 10.1109/LCOMM.2018.2808292.

Abstract: Among the multiple faults that might happen in a cellular network, operators spend long time trying to identify swapped sectors, that is, during the network rollout phase, feeders from baseband units to antenna units may result crossed, thus leading to swaps in service areas for different sectors managed by the same radio equipment. In this letter, two different methods are presented in order to automatically detect antenna misconfigurations due to crossed feeders. Results show that the proposed methods are valid for troubleshooting of swapped sectors, thus saving operator's time. Moreover, both methods have been successfully validated on real networks.

6.2 Swapped Sectors Detection on Multi-Layer Networks

[53] O. Kaddoura, J. J. Sánchez-Sánchez, I. Serrano and R. Barco, "Swapped Sectors Detection on Multi-Layer Networks," in IEEE Communications Letters, vol. 22, no. 11, pp. 2342-2345, Nov. 2018.
DOI: 10.1109/LCOMM.2018.2867846.

Abstract: A common fault in mobile communications networks is the presence of swapped sectors. This is, coverage areas of two or more co-located sectors are swapped. The reason of swapped sectors existence is the interchange of feeders' connections from baseband units or radio units to antennas' ports. In particular, this problem has a greater impact on multi-layer networks, where a higher number of feeder connections are performed per site. In this letter, a method is presented to automatically detect swapped sectors using mobility statistics on multi-layer networks. Simulations have been carried out, proving that the proposed method outperforms other state-of-the-art methods. Furthermore, the proposed method has been validated in three different real LTE networks.

6.3 Swapped Sectors Detection Based on User Location During Inter-Site Handovers

[54] O. Kaddoura, J. J. Sánchez-Sánchez, I. Serrano and R. Barco, "Swapped Sectors Detection Based on User Location During Inter-Site Handovers," in IEEE Access, vol. 7, pp. 92547-92560, 2019.
DOI: 10.1109/ACCESS.2019.2927607.

Abstract: Network roll-out is a process composed of several actions, which, if not completed correctly, may degrade the final system performance. A common error during the roll-out process is the case in which feeders from baseband units to radio units or feeders from radio units to antennas are interchanged. Consequently, in sectorized sites, the service areas of two or more co-sited cells become swapped, affecting the initial network design. This paper proposes to utilize the location of the user during mobility procedures to enhance the state-of-the-art methods to detect swapped sectors automatically. There are multiple solutions to obtain the location of subscribers in mobile communications networks. However, the most accurate ones are either costly or not possible in current networks. Therefore, this paper addresses the problem of applying time-of-arrival techniques based on multilateration in present-day mobile networks by proposing an alternative using standardized signaling. One of the main benefits of the proposed method is its ease of being implemented in real networks without adding additional costs to the operators. Finally, the results are presented to demonstrate that the proposed method improves the performance of state-of-the-art methods.

6.4 Edge Sectors Detection in Mobile Communications Networks

[55] O. Kaddoura, I. Serrano, J. J. Sánchez-Sánchez and R. Barco, "Edge Sectors Detection in Mobile Communications Networks," 2019 European Conference on Networks and Communications (EuCNC), 2019, pp. 586-591.
DOI: 10.1109/EuCNC.2019.8801977.

Abstract: This paper proposes a method to detect edge sectors in mobile communication networks. This detection has applications such as identifying results of geolocation techniques presenting low accuracy or reducing false positives in troubleshooting algorithms. On the way to achieve the desired goal, the method also finds the nodes which are part of convex and concave regions in the contour of the network. The proposed method consists of three phases: independent areas identification, contour nodes detection and edge sectors detection. All these phases can be parameterized according to the pursued objective. Experiments have been carried out to prove the goodness of the proposed method to detect sectors in which location techniques like Received Signal Strength used to estimate the location of mobile users present high error figures. Results obtained prove the validity of the proposed method.

Chapter 7

Conclusions

This last chapter presents a summary of the research conducted in this thesis. The chapter is divided into three sections. The first one reviews the main objectives tackled in this thesis by extracting several conclusions from them. The second one describes future lines of research that could continue the study carried out in this thesis. Finally, the last section presents the main publications in journals, conferences, patents and stays derived from the production of this thesis.

7.1 Contributions

The purpose of this thesis is providing solutions for existing open problems in the area of SON. Specifically, challenges in the three main concepts of SON have been identified and required objectives in order to solve them have been defined. In total, eight objectives have been defined. Two of these objectives are related to self-configuration (Objective 1 and 2), one is related to self-optimization (Objective 3), four are related to self-healing (Objective 4, 5, 6 and 7) and, lastly, an objective aims at implementing the solutions proposed by this thesis into commercial tools. Hereunder, all the contributions related to these objectives are presented.

- **Objective 1**. To find optimal locations for network BSs and antennas of CPEs in 5G FWA networks.

  - A new cost function for FWA planning activities has been proposed. In classical FWA cost function, all the locations where the CPE antenna could be located contribute to the final cost. However, unlike classical FWA cost function, the proposed FWA cost function considers all CPE antenna locations in a household as candidate locations so that the location minimizing the final cost is determined as the location where to deploy the CPE antenna in order to maximize system performance.
  - An exercise using real data from a suburban environment has been carried out in order to assess the proposed FWA cost function. For this exercise, theoretical 5G RF propagation models for band n257 [56] have been calibrated using measurements taken from DT activities. This exercise aimed at finding the best locations where to deploy network equipment in a 5G FWA network in order to maximize a set of targeted KPIs in coverage, dominance and capacity.
  - Moreover, the proposed FWA cost function has been evaluated against the classical FWA cost function. From this comparison, the proposed FWA cost function has shown to improve the results obtained with the classical cost function in two directions: resulting network KPIs are improved and the number of required BSs to deploy is lower.

- **Objective 2**. To find a greenfield design methodology that improves state-of-the-art methodology for selecting the configuration of antenna parameters such as azimuth, electrical tilt or mechanical tilt that maximizes the performance in 5G FWA networks.

  - Unlike the state-of-the-art methodology for greenfield design activities in which network planning and network configuration phases are executed independently one after the other, an iterative methodology that combines both these phases has been proposed.
  - As for objective 1, an exercise using real data from a suburban environment has been carried out in order to assess the proposed iterative methodology. Again, the same theoretical 5G RF propagation models for band n257 and calibrated using measurements taken from drive test

activities have been used. This exercise aimed at finding the best antenna azimuth configurations in a 5G FWA network in order to optimize coverage, dominance and capacity KPIs.

  - The results obtained from this exercise have been compared against state-of-the-art greenfield design methodology. This comparison has proved that the proposed methodology results in better figures of network KPIs while the number of required BSs to be deployed is decreased.
  - Additionally, the proposed methodology can be subsequently used in order to adapt FWA networks to the eventual changes of the RF environment.
  - Furthermore, this iterative methodology could be extended to any kind of greenfield design exercise of mobile communication networks.

- **Objective 3**. To develop a methodology that calibrates RF propagation models based on predictions with the aim of using them in network optimization exercises.
  - A methodology that enables the characterization of the RF propagation channel in LTE and 5G networks has been proposed. This methodology is based on CM and PM standardized information and allows operators to avoid carrying out DT activities.
  - This methodology provides signal distributions per cell and signal to interferer distributions per pair of cells which can be used to calibrate theoretical LTE and 5G RF propagation models so that they describe the reality more accurately.
  - The proposed methodology utilizes gaussian distributions in order to model the output distributions.
  - The proposed methodology utilizes statistics generated from the behavior of all network subscribers. Therefore, the model output by the proposed methodology is more complete than the one provided by DT since subscribers found in locations where DT would not perform measurements (e.g., buildings, pedestrian streets, etc.) are also considered.

Consequently, the model generated by this methodology is more significant than the one generated by DT since only actual locations of subscribers are being considered.

- The proposed methodology can be implemented either as part of the OSS to enhance centralized SON algorithms or as part of the BS to enhance distributed SON functionalities.

- **Objective 4**. To design a framework capable of detecting swapped sectors.
  - A framework which uses CM information (i.e., the location of the cells, the expected azimuth of the antennas and the beamwidth of the antennas) as well as PM information (i.e., mobility statistics such as number of attempted and executed handovers per cell relation) in order to detect swapped sectors in LTE and 5G networks has been designed.
  - The proposed framework is divided into two different techniques: a technique based on inter-site mobility and a technique based on intra-site mobility. The first technique utilizes the location of the cells and their neighbors in order to find an averaged direction in which their subscribers can be found based on their mobility patterns. This direction is later compared against the expected azimuth of the antenna of the sector to find big deviations. The second technique of this framework uses intra-site mobility among different frequency carriers in order to find unexpected mobility patterns that could indicate that the azimuth of the antenna of a sector is not pointing to the expected direction.
  - Additionally, criteria based on the necessary condition of finding azimuth deviations for two sectors in case of swapped pairs and for three sectors in case of rotated trios have been added to the framework.
  - Two different simulators have been used in order to validate this framework. More than a million simulations using different network configurations have been performed in order to eliminate any bias due to network configuration or random mobility patterns. Simulations have been configured so that swapped sectors are forced. Finally, mobility statistics have been extracted to be used by the framework.

  - Two indicators have been used in order to assess the proposed framework: true positives rate (i.e., correctly detected swapped cases divided by the total number of swapped cases) and false positives rate (i.e., wrongly detected cases divided by the number of potential cases in the network). Based on these indicators, the proposed framework has been proved to outperform other state-of-the-art methodologies.
  - The technique based on intra-site mobility has provided the best results. However, the applicability of this technique is limited to BSs having at least two different frequency layers. However, the technique based on inter-site handovers can be used in any BS.
  - Moreover, the proposed framework has been evaluated using data from real LTE networks. Since drive testing is the standardized methodology to detect swapped sectors, drive testing activities have been carried out in order to prove the validity of the proposed framework as a good replacement to these. These activities have confirmed as actual swapped sectors those cases initially detected by the framework.

- **Objective 5**. To develop a technique capable of positioning subscribers in LTE and 5G networks with a higher precision than the current methods based on default functionalities.

  - An estimator of UE location based on ToA techniques has been proposed. This estimator combines information extracted from TA and MR messages standardized in LTE and 5G networks. Therefore, its applicability is universal for these networks.
  - Data from a commercial LTE network has been used in order to validate the proposed estimator. Specifically, WT activities have been performed in order to determine the actual location of the UE. The International Mobile Subscriber Identity (IMSI) values used during these WT have been used in order to find their corresponding messages among all the signaling messages extracted from the OSS.
  - All collected data has been useful to determine the accuracy of the proposed estimator. The obtained accuracy has been compared with

the accuracy of other positioning techniques available in this network, resulting the proposed estimator as the best positioning technique.

- **Objective 6**. To combine Objective 4 and Objective 5 to improve the success rate of swapped sectors detection techniques.

  - The methodology based on inter-site mobility statistics proposed in Objective 4 has been enhanced using UE positioning techniques. Initially, this methodology used the location of the handover target cell as the location where the handover procedure is performed. However, the utilization of UE positioning techniques in order to estimate the actual location where the handover procedure is carried out is proposed now.
  - Mobility statistics data have been extracted from a commercial network and modified in order to simulate the presence of swapped sectors. Subsequently, different UE positioning techniques have been used to determine the positions at which handover procedures have been performed. Thus, swapped sector detection methodology has been enhanced using these positions.
  - Results have concluded that using positioning techniques in order to identify the actual location where the handover procedure is performed improves both true positives rate and false positives rate of the proposed swapped sector detection methodology based on inter-site mobility.

- **Objective 7**. To find a methodology capable of reducing the number of false positives in swapped sectors detection.

  - A methodology aimed at identifying edge sectors in a mobile communication network has been proposed. That is, a methodology that identifies those cells located at the boundaries of a network and having the azimuth of their antennas pointing outside of the network core.
  - A set of simulations has been performed to evaluate the proposed methodology. Specifically, Received Signal Strength (RSS) positioning technique, which presents worse accuracy figures when subscribers are served by edge sectors, has been used as benchmark. Simulations have successfully proved that the proposed method properly identifies edge sectors,

since overall accuracy figures are improved when the detected cells are not considered.

- The proposed methodology can be applied to any use case that requires from identifying edge sectors. Therefore, since swapped sectors detection methodology based on inter-site mobility is prone to fail for edge sectors, where handover location will be wrongly estimated, this methodology is suitable for discarding these sectors from detected cases. Thus, the number of false positives can be reduced.

- **Objective 8**. To implement all the developed methods, techniques and algorithms in existing commercial planning, optimization and troubleshooting tools.

  - Ericsson Network Design and Optimization portfolio has been enhanced with the addition of new modules which include the functionalities studied and proposed in this thesis. Specifically, *Ericsson RAN Analyzer*, *Ericsson Cell and Frequency Optimizer* and *Ericsson Cognitive Software* are the commercial tools and platform that now include these functionalities.

7.2 Future work

The present thesis has explored and contributed to the state of the art of different lines of research. However, all these lines of research could be continued as proposed hereunder:

- A methodology to carry out greenfield design activities for FWA networks has been proposed. This methodology is focused on the radio access interface, trying to find the best locations where to deploy BSs in order to improve final network performance. However, transport network could also be considered in order to select the locations where to deploy BSs so that the CAPEX and OPEX of optical fiber deployment are minimized.

- A methodology to build signal distributions per cell and signal to interferer distributions per pair of cells based on standardized functionality available in LTE and 5G networks has been presented. The proposed method is valid to find one point of each cumulative distribution function. This would be enough for distribution functions characterized by a single parameter. However, distribution functions are usually characterized by two parameters. As an example, gaussian distributions are described by two parameters, mean and variance. Therefore, a second point is required to calculate these two parameters. A next line of research should study a methodology in order to find the probability function that better fits the real distribution as well as the remaining parameters that characterize it.

- A framework has been designed in order to detect swapped sectors in LTE and 5G mobile communication networks. This framework is valid to identify cases in which both transmission and reception cables are connected to wrong antennas. However, it could be the case that only one of the feeders of a cell is swapped with one of the feeders of a different cell. This is a rare scenario, since usually feeders are paired during the installation process. However, this problem is worth studying.

- The framework proposed to detect swapped sectors is composed of different techniques. These techniques have been evaluated separately and the advantages of each one of them have been presented. However, these techniques could be combined in such a manner that the final detection effectiveness is improved.

- A methodology to detect edge sectors in mobile communication networks has been proposed and validated using UE positioning techniques. This methodology can be used to decrease the number of false positives in swapped sectors detection techniques. Therefore, a further analysis to detail the exact impact this methodology has over the reduction of false positives in swapped sectors detection techniques needs to be done.

7.3 Outcomes

This section presents the contributions and activities derived from the elaboration of this thesis.

7.3.1 Publications in Journals

Five publications in high impact journals have been derived from this thesis. This publications are listed in Table 7.1.

TABLE 7.1: Publications.

	Publication	**IF**	**Journal Rank**
I	O. Kaddoura et al. "Greenfield Design in 5G FWA Networks" IEEE Communications Letters vol. 23, no. 12, pp. 2422-2426, Dec. 2019 doi: 10.1109/LCOMM.2019.2939470	3.419	Q2 (32/90) Telecommunications
II	O. Kaddoura, J. Outes, J. J. Sánchez-Sánchez and R. Barco "Radio Frequency Footprint Characterization Based on Mobility Indicators" IEEE Wireless Communications Letters Sep. 2020 doi: 10.1109/LWC.2020.3023283	4.660	Q1 (2019) (17/90) Telecommunications
III	O. Kaddoura, R. Barco, I. Serrano and J. J. Sánchez-Sánchez "Swapped Sectors Detection Based on Mobility Statistics" IEEE Communications Letters vol. 22, no. 5, pp. 1038-1041, May 2018 doi: 10.1109/LCOMM.2018.2808292	3.457	Q2 (28/88) Telecommunications
IV	O. Kaddoura, J. J. Sánchez-Sánchez, I. Serrano and R. Barco "Swapped Sectors Detection on Multi-Layer Networks" IEEE Communications Letters vol. 22, no. 11, pp. 2342-2345, Nov. 2018 doi: 10.1109/LCOMM.2018.2867846	3.457	Q2 (28/88) Telecommunications
V	O. Kaddoura, J. J. Sánchez-Sánchez, I. Serrano and R. Barco "Swapped Sectors Detection Based on User Location During Inter-Site Handovers" IEEE Access vol. 7, pp. 92547-92560, 2019 doi: 10.1109/ACCESS.2019.2927607	3.745	Q1 (61/266) Engineering, electrical & electronic

7.3.2 Conferences

Table 7.2 summarizes the list of conferences arising from this thesis.

Table 7.2: Conferences.

	Conference
VI	O. Kaddoura, I. Serrano, J. J. Sánchez-Sánchez and R. Barco "Edge Sectors Detection in Mobile Communications Networks" 2019 European Conference on Networks and Communications (EuCNC), Valencia, Spain 2019, pp. 586-591 doi: 10.1109/EuCNC.2019.8801977
VII	O. Kaddoura, I. Serrano and R. Barco "Detección de sectores borde en redes de comunicaciones móviles" XXIV Simposium nacional de la Unión Científica Internacional de Radio, Valencia, 2014

7.3.3 Patents

Table 7.3 lists the patent derived from this thesis.

Table 7.3: Patents.

	Patent
VIII	O. Kaddoura, J. Outes and G. Payo "Method and Apparatus for Characterizing a Radio Frequency Environment in a Telecommunications Network" 03.10.2019 PCT/EP2018/057995

7.3.4 Collaboration with the industry

This thesis has been carried out in collaboration with Network Design and Optimization group of Ericsson. Therefore, all the solutions derived from this thesis have been implemented as part of Ericsson Network Design and Optimization commercial tools such as *Ericsson RAN Analyzer*, *Ericsson Cell and Frequency Optimizer* and *Ericsson Design and Optimization Platform*.

7.3.5 Research stays

As part of this thesis, four international stays were carried out at several Ericsson premises in U.S.A and India with a total duration of 92 days. These stays are detailed in Table 7.4.

TABLE 7.4: Research stays.

	Research Area	**Location**	**Duration**
i	Radio Network Optimization	Plano, Texas. U.S.A.	12/11/2014 - 04/12/2014 23 days
ii	Radio Network Optimization	Irvine, California. U.S.A.	22/06/2015 - 03/07/2015 12 days
iii	Radio Network Optimization	Irvine, California. U.S.A.	06/06/2016 - 24/06/2016 19 days
iv	AI Intelligent Autonomous Systems	Bengaluru. India	03/09/2019 - 10/10/2019 38 days

Appendix A

Summary (Spanish)

A.1 Introducción

A.1.1 Antecedentes y justificación

Con el paso de los años, el campo de las comunicaciones móviles ha experimentado un gran crecimiento. Los dispositivos móviles han sufrido cambios desde sus orígenes y, hoy en día, no son únicamente un mero medio de comunicación entre personas. Su accesibilidad a Internet ha hecho que sean usados para actividades como visionado de vídeos, control remoto, monitorización, lectura de libros, compras, almacenaje de datos en la nube o aprendizaje. Además, con la llegada del Internet de las cosas (*Internet-of-Things* en inglés), el número de subscriptores ha aumentado. En 2019, excedieron los 8 billones y representaron un 108 % de la penetración global [1]. Por tanto, ya existen más subscriptores que habitantes en la Tierra.

La aparición de nuevos dispositivos móviles demandando nuevos servicios ha forzado a que las tecnologías móviles evolucionen, lo que ha conducido a una complejidad mayor en las redes móviles. Las redes móviles han de satisfacer las altas tasas demandadas, la conectividad masiva y las bajas latencias a la vez que se garantice la alta calidad de servicio requerida por los usuarios. Hoy en día, las redes de 5ª Generación son la tecnología comercial más avanzada de redes de comunicaciones móviles [2].

Debido a la complejidad de las redes actuales, los operadores móviles se ven obligados a invertir una gran cantidad de recursos tanto en actividades de despliegue como de mantenimiento. Además, la alta competitividad del mercado añade presión a los operadores, quienes tienen que reducir los precios de sus productos. Por tanto, para asegurar la viabilidad de sus proyectos, los operadores persiguen minimizar sus gastos capitales y operacionales. Es decir, los operadores móviles buscan encontrar un balance entre la maximización de beneficios con precios más bajos y la prestación de servicios de alta calidad a sus subscriptores.

En este contexto, la alianza *Next Generation Mobile Networks* especificó las redes auto-organizadas (*Self-Organizing Networks* (SON) en inglés) como una solución a la automatización de la planificación, despliegue, optimización y mantenimiento de las redes móviles de 4ª generación [3, 4]. Más tarde, el organismo *3rd Generation Partnership Project (3GPP)* incorporó las ideas de las SON y las aplicó a sus estándares [5]. Este concepto se introdujo con la intención de aumentar la inteligencia de las redes de forma que las tareas manuales fuesen automatizadas y se redujeran costes. Desde que los conceptos de redes auto-organizadas fuesen introducidos, se han convertido en un requisito obligatorio en las redes de comunicaciones móviles y un tema de continuo interés en la investigación [6, 7, 8, 9, 10, 11].

En particular, 3GPP dividió las funcionalidades las SON en tres categorías principales [5, 12]:

- Auto-configuración [13]. La auto-configuración se divide en las fases de planificación y despliegue.
    - La fase de planificación consiste en el diseño de nuevos elementos a añadir en la red. Es decir, encontrar la localización en la que se instalarán estos y la configuración de sus parámetros de forma que la cobertura, capacidad e interferencia en la red sean óptimas.
    - La fase de despliegue persigue la configuración automática de los nuevos elementos de la red así como de los ya existentes. Es decir, cuando una

nueva estación base se introduce en la red, ésta es reconocida inmediatamente por el resto de elementos de la red y registrada.

- Auto-optimización [13]. Debido a los cambios meteorológicos, los diferentes patrones de tráfico o las interferencias externas, las condiciones de las redes son estocásticas. Así, la auto-optimización se encarga de ajustar los parámetros de la red de forma que siempre se consiga un rendimiento óptimo. La auto-optimización se puede dividir en las fases de monitorización, análisis y acción.
  - Monitorización: Se extraen una serie de indicadores de rendimiento de la red.
  - Análisis: Se proponen cambios en los parámetros de la red en base a los indicadores de rendimiento de la red.
  - Acción: Se implementan los cambios propuestos en los parámetros de la red.
- Auto-curación [14]. Una vez que las redes están operativas, éstas pueden sufrir degradación en su rendimiento debido a problemas en su software o hardware. Para mitigar ésto, la auto-curación incluye cuatro fases.
  - Detección de fallos. Se detectan problemas en base a las estadísticas de rendimiento de la red.
  - Compensación. Se realizan acciones para mitigar la degradación del rendimiento de la red.
  - Diagnóstico de fallos. Se identifica la raíz del problema.
  - Reparación. Se corrige el problema que produce la degradación.

Debido a la necesidad de incluir los conceptos de SON a las redes de comunicaciones móviles, varios proyectos para investigar, desarrollar e industrializar las técnicas de SON en redes 4G y 5G fueron lanzados. Entre estos, se encuentran UniverSelf [15], SELFNET [16], COMMUNE [17], SEMAFOUR [18], FP7 E3 [19], CELTIC Gandalf [20], FP7 SOCRATES [12], CSON [21], QSON [22] y SELFNET-5G [23]. Sin embargo, a pesar de toda la investigación realizada en SON, todavía existen áreas en las que se necesita un análisis más profundo ya sea porque éstas no han sido cubiertas en toda la extensión necesaria o porque, debido a que la tecnología ha continuado evolucionando, han surgido nuevas áreas susceptibles de automatización. Se pueden encontrar ejemplos de estas áreas en todas las categorías de SON. A continuación, se presenta un área carente de una investigación más extensa para cada categoría de SON.

Con la intención de aplicar los conceptos de SON a las redes de comunicaciones móviles, estas redes proporcionan información acerca de su configuración o de su rendimiento a través de varios interfaces. Estos interfaces se conocen como gestión de la configuración (*Configuration Management* (CM) en inglés), gestión del rendimiento (*Performance Management* (PM) en inglés) o trazas móviles (*Mobile Traces* (MT) en inglés). CM proporciona información sobre la configuración de la red tal como la localización de las celdas, configuraciones de azimut, configuraciones de potencia, umbrales de traspasos, etc. PM proporciona información sobre el rendimiento de la red. La información de rendimiento es comúnmente agregada a niveles de celda o relaciones y contiene valores de indicadores de rendimiento (*Key Performance Indicators* (KPIs) en inglés) tales como el número de llamadas cursadas, el número de llamadas caídas, el número de traspasos, etc. Por último, MT proporciona información sobre mensajes de señalización enviados entre los elementos de la red y los dispositivos móviles. Todos estos interfaces son accesibles desde el módulo de gestión de operaciones (*Operations Support System* (OSS) en inglés) de la red móvil.

Con la llegada de las redes 5G y las tasas de datos que garantizan, las redes de acceso radio fijo [24](*Fixed Wireless Access* (FWA) en inglés), diseñadas para acercar el acceso a Internet de banda ancha a los hogares, han surgido como la mejor alternativa a las tecnologías fijas. FWA consiste en el reemplazo del último kilómetro de cable por el interfaz aire, de forma que un sólo transceptor sea capaz de proporcionar acceso de banda ancha a una serie de hogares provistos de equipos especiales (*Customer Premises Equipment* (CPE) en inglés). Como parte de la categoría de auto-configuración en SON, la fase de planificación pretende encontrar la mejor configuración de red que satisfaga las necesidades de tasas de datos de los subscriptores a la vez que minimice los costes del despliegue y mantenimiento de la red. Los métodos actuales de planificación de redes FWA persiguen la optimización de la configuración RF para el edificio por completo, en vez de la localización en la que se instalará la antena del CPE. Esto conduce a redes subóptimas en las que el rendimiento de la cobertura e interferencia se ve dañado.

Como parte de las funcionalidades de auto-optimización, la huella RF es modelada de forma precisa de modo que el efecto que provoca la modificación de los parámetros de red sobre el rendimiento de ésta pueda ser anticipado. Los operadores móviles generalmente usan medidas empíricas tomadas a través de mediciones en vehículo (*Drive Test* (DT) en inglés) o mediciones a pie (*Walk Test* (WT) en inglés) [25] con la intención de generar modelos de huella RF de la red, ya que éstos proporcionan mayor precisión que la de los modelos teóricos. Sin embargo, los DT son caros y, en ocasiones, los operadores utilizan MT [26] y Minimización de DT (*Minimization of Drive Tests* (MDT) en inglés) [27, 28, 29, 30], que proporcionan medidas RF y su correspondiente información de localización. No obstante, estas funcionalidades no siempre están disponibles en las redes comerciales y, además, sus medidas pueden producir resultados incompletos debido a la naturaleza de la recolección de muestras [31]. Por tanto, los operadores móviles requieren de un método capaz de construir modelos de huella RF completos basándose en funcionalidad estandarizada en las redes en vez de en funcionalidades que, o bien no están disponibles en redes comerciales o bien sus licencias son demasiado caras.

El despliegue de una red de comunicaciones móviles es un proceso en el que se ejecutan numerosas acciones. Algunas de estas acciones son llevadas a cabo por ingenieros y, por tanto, son susceptibles al error humano. Por tanto, el rendimiento final de una red podría verse degradado si un fallo fuese cometido durante el proceso de despliegue. Un error común en el despliegue de redes de comunicaciones móviles es el caso en el que los cables que van desde las unidades de banda base (*Baseband Units* (BBU) en inglés) hasta las unidades de radio (*Radio Units* (RU) en inglés) o los cables que van desde las RU hasta las antenas son intercambiados. En emplazamientos sectorizados, este error, conocido como sectores intercambiados (*swapped sectors* en inglés) provoca que las áreas de servicio de dos o más celdas colocalizadas estén intercambiadas. Así, debido a la presencia de sectores intercambiados, las redes podrían presentar problemas de cobertura, interferencia o movilidad, entre otros. En la actualidad, los sectores cruzados son detectados a través de DT y WT [25]. Mediante éstos, los ingenieros realizan mediciones de señal en los alrededores de los emplazamientos de modo que puedan generar la huella de señal de los sectores que los conforman. Así, la huella obtenida se compara con la esperada por el diseño de la red y se identifican posibles sectores intercambiados. Esta actividad de detección de fallos podría ser automatizada y formar parte de la categoría de auto-curación en SON.

Por consiguiente, esta tesis contribuye al estado del arte incrementando las funcionalidades de SON y superando las limitaciones de los anteriores casos de uso para, así, reducir las distancias en la automatización de redes.

A.1.2 Retos y objetivos

El objetivo principal de esta tesis es superar limitaciones en varios casos de uso que pertenecen a cada una de las categorías que componen las SON. Por tanto, los retos y objetivos de esta tesis se agrupan en tres categorías: auto-configuración, auto-optimización y auto-curación. Estos retos han sido identificados en colaboración con el grupo *Network Design and Optimization* perteneciente a la empresa Ericsson, quiénes necesitan encontrar soluciones a problemas para los cuáles aún no las hay.

En el contexto de la auto-configuración, los operadores móviles persiguen diseñar redes capaces de satisfacer los requisitos de sus usuarios y proporcionarle a éstos la mejor experiencia posible. Para ello, normalmente los operadores móviles se centran en tres KPIs: cobertura, dominancia y capacidad. Cobertura hace referencia a la capacidad de la red en proporcionar un nivel de señal mínimo a sus subscriptores de modo que éstos puedan ser servidos. Dominancia hace referencia a la interferencia que experimenta un subscriptor desde celdas no servidoras. Idealmente, un subscriptor no debe observar interferencia de celdas vecinas excepto en las áreas en las que la cobertura está comprometida (éstas son las áreas dónde se realizan los procedimientos de movilidad). Capacidad hace referencia a la capacidad de la red en proporcionar servicio a todos los usuarios que solicitan recursos de forma simultánea. Tanto la cobertura, la dominancia como la capacidad pueden ser mejoradas añadiendo más estaciones base a la red. Sin embargo, la adición de estaciones base aumenta el coste de despliegue y mantenimiento de la red. Por tanto, los operadores móviles intentan maximizar los KPIs de la red a la vez que se mantenga al mínimo el número de elementos de red requeridos para garantizar una QoS adecuada. Actualmente, los operadores móviles utilizan herramientas de planificación para diseñar sus nuevos despliegues. Estas herramientas hacen uso de modelos de propagación y patrones de antena para estimar la huella de señal de cualquier nueva estación base a desplegar. Estas herramientas son válidas para despliegues normales en los que se espera que los subscriptores se muevan con libertad.

Sin embargo, las herramientas de planificación no han sido mejoradas para permitir el diseño de redes FWA 5G. Este reto es abordado en esta tesis a través de dos objetivos. **El primer objetivo consiste en encontrar la localización óptima de las estaciones base y los CPE a desplegar en la red** (Objetivo 1). Es decir, entre todas las localizaciones posibles en las que se pueden desplegar las estaciones base y las localizaciones posibles donde se pueden instalar las antenas de los CPE en los hogares, encontrar aquellas que minimizan el equipo necesario a desplegar a la vez que se maximicen los KPIs de la red. **El segundo objetivo consiste en encontrar la configuración óptima de parámetros de red como el azimut de las antenas, sus tilts mecánicos, tilts eléctricos o potencias de transmisión** (Objetivo 2).

En el contexto, de auto-optimización, los operadores móviles realizan continuas optimizaciones del rendimiento de la red de forma que ésta se adapte a los diversos cambios del entorno RF. Un ejercicio común de optimización es el conformado de radiofrequencia (*radio frequency shaping* en inglés). El conformado de radiofrecuencia consiste en la modificación de parámetros de antena tales como azimuts, tilts mecánicos y tilt eléctricos de forma que la huella de señal de las celdas de la red se vea modificada con el objetivo de mejorar los indicadores de cobertura e interferencia. Métodos asistidos por ordenador conocidos como planificación automática de celdas (*Automatic Cell Planning* (ACP) en inglés) [32] surgieron para ayudar a los ingenieros a realizar estas actividades de optimización. Estos métodos implementan algoritmos de optimización metaheurísticos [33] para encontrar la configuración de parámetros que resulte en el mejor rendimiento de la red. Estos algoritmos se basan en la evaluación de una función de coste dependiente del nivel de señal recibido por cada subscriptor en la red desde todas las celdas que le rodean. Por tanto, es importante alimentar a estos algoritmos con un modelo de propagación RF completo que les permita recalcular el nivel de señal recibido por un subscriptor cuando un parámetro de antena se ve modificado.

Con este propósito, los operadores móviles a menudo realizan campañas de DT [25] en las que los ingenieros de campo realizan mediciones de los niveles de señal de las celdas que componen la red recibidos en diferentes localizaciones. Sin embargo, los modelos construidos a través de DT generalmente están incompletos, ya que sólo incluyen medidas en lugares en los que se encuentran subscriptores conduciendo vehículos y no en áreas peatonales. Con la intención de salvar esta limitación, los operadores móviles comenzaron a recolectar MT [26] para calibrar modelos básicos de propagación RF basados en predicciones [34]. No obstante, no todos los fabricantes de equipos de red incluyen en sus equipos la funcionalidad necesaria para recolectar MT y, cuando lo hacen, en ocasiones sus costes son muy elevados. Por consiguiente, esta tesis proporcionará **un nuevo enfoque por el cual calibrar modelos básicos de propagación RF basados en predicciones mediante el uso de funcionalidad estandarizada disponible en todos los fabricantes sin coste adicional** (Objetivo 3).

En el contexto de auto-curación, las redes móviles, como sistemas complejos que son, están expuestas a experimentar fallos. Debido a esto, los operadores móviles han de tener mecanismos para identificar estos fallos de forma que se puedan tomar acciones para corregirlos. Habitualmente, los fabricantes incluyen sistemas de alarma en sus equipos de modo que el administrador de la red es notificado cuando se produce un fallo. Además, normalmente estas alarmas vienen acompañadas de sugerencias de resolución del problema. Existen casos en los que los equipos de red funcionan según lo esperado pero que, debido al comportamiento de los subscriptores, el rendimiento de la red se ve degradado. En estos casos, detectar que un problema en la red está ocurriendo es tan simple como comprobar que existe una degradación en los KPIs de rendimiento de ésta. No obstante, existen algunos casos en los que un rendimiento incorrecto de la red podría pasar desapercibido. Se trata de casos en los que el problema existía desde que la red fue desplegada. En estos casos, la red opera con normalidad. Sin embargo, la red móvil tiene un problema que si fuese subsanado haría que ésta mejorara su rendimiento. Los mecanismos de auto-curación están diseñados para tomar acciones correctivas para solucionar o mitigar estos problemas. En concreto, los sectores intercambiados, en los que la señal que se espera radiar por una antena es en realidad radiada por una antena diferente, es uno de estos casos. El problema se origina cuando los ingenieros de campo intercambian los cables que conectan la BBU con las RU o los que conectan las RU con las antenas de un emplazamiento. Una red que contenga sectores intercambiados podría manifestar degradación en los procedimientos de movilidad debido a incorrectas listas de vecinas o conflictos de *Physical Cell Identity* (PCI), degradación de las tasas de datos debido a problemas de alta interferencia o el aumento de llamadas caídas debido a la aparición de agujeros de cobertura.

Para detectar sectores intercambiados, los operadores móviles generalmente realizan campañas de DT en las que los ingenieros de campo realizan medidas de señal alrededor de las estaciones bases de la red y comparan estas medidas con lo esperado si no existiesen sectores intercambiados. Como reto, esta tesis intenta encontrar una solución automática basada en indicadores de rendimiento de la red capaz de detectar sectores intercambiados con una alta tasa de acierto y evitando los costes por la realización de campañas de DT. **Esta tesis perseguirá la detección de sectores intercambiados a través de la utilización de estadísticos de movilidad en redes LTE y 5G con la intención de calcular la dirección a la que es radiada la señal de cada celda de la red** (Objetivo 4).

El objetivo anterior puede ser mejorado a través de la utilización de **técnicas de posicionamiento que permitan identificar la localización real de los subscriptores de la red cuando se origina un procedimiento de traspaso** (Objetivo 6). Con este propósito, en esta tesis se estudiará **una nueva técnica de posicionamiento aplicable en cualquier red LTE y 5G comercial** (Objetivo 5). La tasa de éxito de cualquier técnica de detección se puede medir en base al número de verdaderos y falsos positivos y negativos. En particular, en el ámbito de los sectores intercambiados, reducir el número de falsos positivos es crítico ya que corregir los sectores intercambiados implica visitar la localización de la estación base. Por tanto, esta tesis investigará **una metodología capaz de reducir el número de falsos positivos de los algoritmos de detección de sectores intercambiados propuestos** (Objetivo 7).

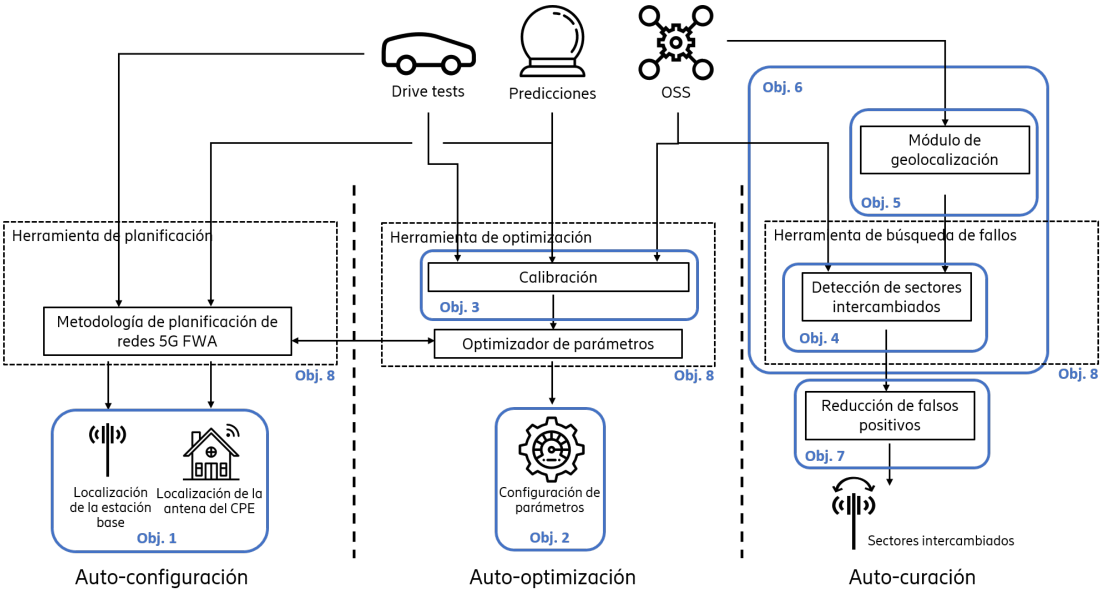

FIGURA A.1: Objetivos de esta tesis.

Todos estos objetivos tienen en común la necesidad de **resolver problemas en redes comerciales**. Así, las soluciones derivadas de esta tesis tendrán que ser lo suficientemente simples como para poder ser fácilmente implementadas en redes comerciales sin necesidad de modificar los elementos que las componen.

Por último, **como el grupo *Network Design and Optimization* de Ericsson usa herramientas propietarias para llevar a cabo ejercicios de diseño, de optimización y de diagnóstico de problemas, todas las soluciones a los anteriores retos serán integradas en estas herramientas** (Objetivo 8) de forma que puedan ayudar a los operadores móviles a automatizar procesos y reducir costes.

Todos estos objetivos están representados en la Fig. A.1.

En resumen, los objetivos que pretenden resolver los anteriores retos son los siguientes:

- Objetivo 1. Encontrar la localización óptima en la que desplegar las estaciones base y antenas de los CPE en redes FWA 5G. Estas localizaciones se elegirán en base al impacto que tengan en los indicadores de rendimiento de la red.

- Objetivo 2. Encontrar un metodología que mejore el estado del arte en la elección de la configuración de parámetros de antena tales como azimut, tilt mecánico o tilt eléctrico que maximice el rendimiento de redes FWA 5G.
- Objetivo 3. Desarrollar una metodología que calibre modelos de propagación RF basados en predicciones con la intención de usarlos en ejercicios de optimización de redes móviles. Esta metodología debe basarse en funcionalidad estándar disponible en cualquier red LTE o 5G.
- Objetivo 4. Diseñar un sistema capaz de detectar sectores intercambiados. Este sistema encontrará la antena por la que la señal de cada celda está siendo radiada y correlará lo encontrado para detectar casos en los que los cables que conectan las BBU con RU o RU con antenas han sido intercambiados durante el proceso de instalación. Para ello, se usarán indicadores de movilidad disponibles en redes LTE y 5G.
- Objetivo 5. Desarrollar una técnica capaz de posicionar a los subscriptores en redes LTE y 5G con mayor precisión que los métodos actuales basados en funcionalidad básica.
- Objetivo 6. Combinar el Objetivo 4 y Objetivo 5 con la intención de mejorar la tasa de éxito de las técnicas de detección de sectores intercambiados.
- Objetivo 7. Encontrar una metodología capaz de reducir el número de falsos positivos en la detección de sectores intercambiados.
- Objetivo 8. Implementar todos los métodos, técnicas y algoritmos desarrollados en esta tesis en herramientas comerciales de planificación, optimización y búsqueda de fallos como parte de la mención industrial de esta tesis. Por tanto, las soluciones propuestas serán validadas con datos obtenidos de redes reales.

A.2 Descripción de los resultados

En esta sección se presentan todos los resultados derivados de esta tesis y que abordan los objetivos presentados en la sección anterior. La Fig. A.2 hace un resumen de la relación existente entre los resultados y los objetivos, incluyendo la conexión que tienen con los retos identificados en este documento.

A.2.1 Diseño de redes 5G FWA [I] (Capítulo 4)

Tal y como se ha presentado con anterioridad, el Capítulo 4 corresponde al concepto de auto-configuración de SON. Por tanto, esta publicación tiene como finalidad resolver los principales objetivos de esta tesis relacionados con la auto-configuración. Es decir, esta publicación pretende encontrar tanto las mejores localizaciones en las que desplegar las estaciones base como las mejores localizaciones en las que instalar las antenas de los CPE (Objetivo 1), así como encontrar la mejor configuración de los parámetros de red (Objetivo 2).

Para conseguirlo, esta publicación propone una nueva función de coste válida para el diseño de redes 5G FWA que, al contrario que otras funciones de coste del estado del arte, considera que la localización de la antena del CPE será la mejor posible entre todas las localizaciones posibles en el edificio. Por tanto, cualquier otra localización no contribuirá a la función de coste. Esta nueva función de coste permite alcanzar una mejor solución ignorando localizaciones que no afectarán al rendimiento final de la red. Además, esta publicación también propone un algoritmo iterativo que combina funciones de optimización extraídas de soluciones de auto-optimización con la planificación de la red, de forma que las localizaciones finales de las estaciones base son determinadas teniendo en cuenta que el estado actual de la red es el mejor posible. Es decir, en primera instancia se añade una estación base a la red (fase de planificación) para, a continuación, optimizar la configuración de la red (fase de configuración) antes de añadir una nueva estación base.

Este algoritmo resulta en un diseño de red que requiere un menor número de estaciones base respecto al caso en que las fases de planificación y configuración son ejecutadas de forma independiente para alcanzar el rendimiento de red deseado. Para ello, esta publicación hace uso de las siguientes entradas: las localizaciones candidatas en las que desplegar las estaciones base, información sobre las pérdidas

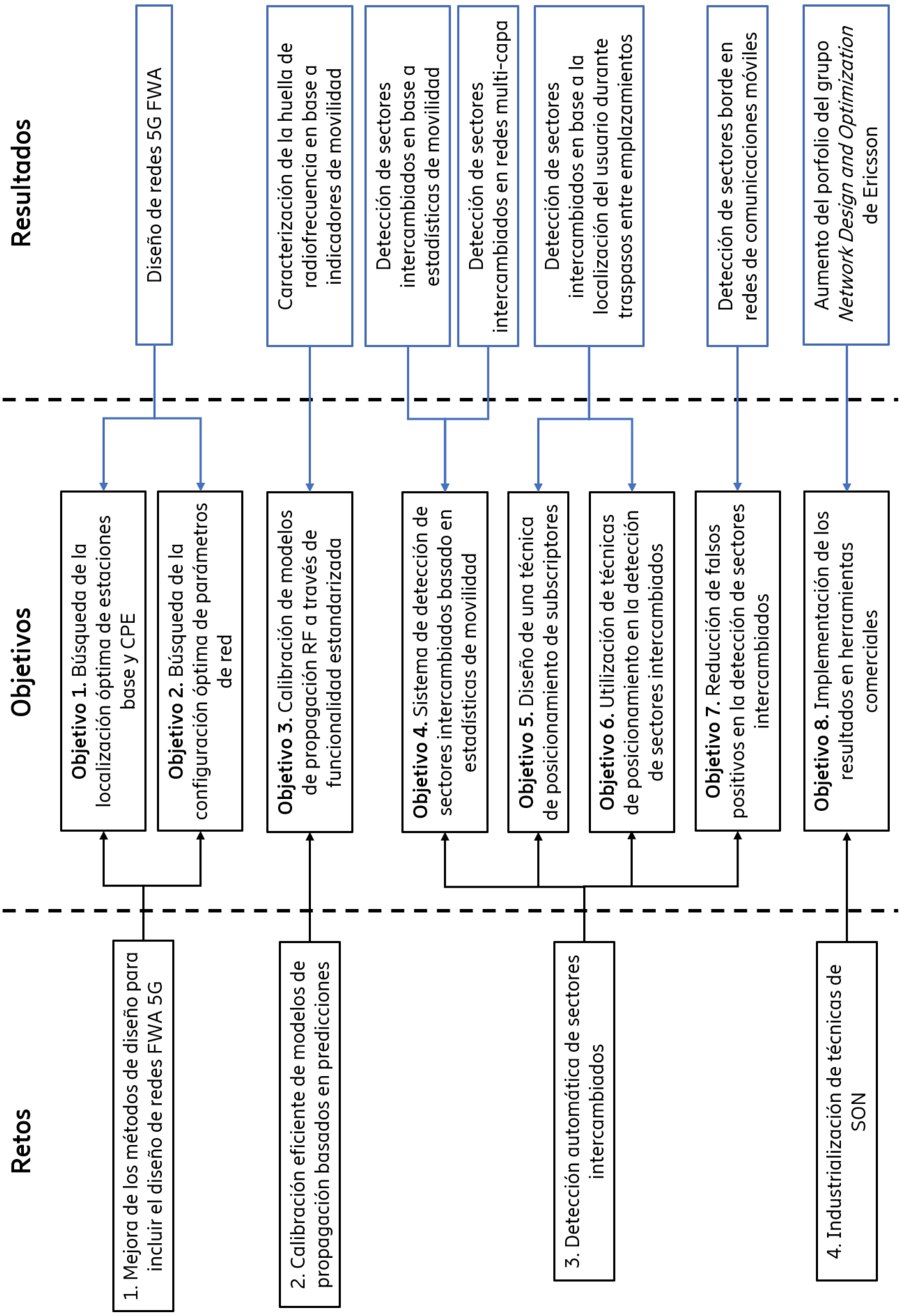

FIGURA A.2: Retos, objetivos y resultados.

de propagación entre estaciones base y CPE, la potencia de transmisión de las antenas y los patrones de radiación de las antenas, entre otras.

La metodología propuesta en esta publicación ha sido evaluada usando datos de un entorno suburbano real. Los resultados demuestran que el rendimiento final de la red mejora con respecto a los métodos del estado del arte mientras que los costes de despliegue (es decir, el número de estaciones base) son reducidos.

A.2.2 Caracterización de la huella de radiofrecuencia en base a indicadores de movilidad [II] (Capítulo 5)

Esta publicación se sitúa en el contexto del concepto de auto-optimización de SON. En particular, esta publicación propone una metodología de calibración de modelos de propagación RF basados en predicciones, utilizando para ello funcionalidad estándar disponible en redes LTE y 5G comerciales (Objetivo 3). Con el fin de conseguirlo, esta publicación presenta una metodología que, utilizando la configuración de parámetros de red así como estadísticas de movilidad, es capaz de generar distribuciones de cobertura e interferencia. En particular, se propone un método que combina la configuración de eventos de movilidad con el número de conexiones y traspasos realizados. Así, se prescinde de la necesidad de ejecutar DT.

La metodología propuesta en esta publicación ha sido evaluada usando datos de una red LTE comercial. Los resultados han probado que esta metodología puede ser considerada como una técnica universal para caracterizar la huella RF.

A.2.3 Detección de sectores intercambiados en base a estadísticas de movilidad [III] (Capítulo 6.1)

Esta publicación, como todas las publicaciones en el Capítulo 6, tiene como finalidad contribuir al estado del arte de técnicas de auto-curación de SON. En particular, esta publicación aborda el objetivo de diseñar un sistema capaz de detectar sectores intercambiados en redes de comunicaciones móviles (Objetivo 5).

Para ello, esta publicación propone y compara dos metodologías novedosas. Ambas metodologías usan como entrada la localización de las estaciones base de la red, los azimuts esperados de los sectores y estadísticas de movilidad como intentos traspasos.

La primera metodología (referida como Método I) propone la identificación de un rango de ángulos (conocido como ángulo sólido) por sector en el cual se espera que se realicen los traspasos de un sector de acuerdo con su configuración de azimut. A continuación, se presenta una función de coste que combina el número de traspasos realizados con la distancia a la que éstos se realizan. Con este propósito, se utiliza la distancia entre la celda origen y la celda destino del traspaso. Esta función de coste se calcula para cada sector con respecto a todos los ángulos sólidos de sectores colocalizados con éste. Es decir, en un emplazamiento dividido en tres sectores, la función de coste se evalúa nueve veces (tres sectores multiplicado por tres ángulos sólidos en el emplazamiento). Finalmente, si la función de coste de mayor valor para un sector no es la que corresponde con su ángulo sólido, se identifica el sector como un potencial candidato a sector intercambiado. En concreto, si la función de coste para la cual se obtiene el mayor valor para un sector corresponde con el ángulo sólido de un sector colocalizado con éste que, a su vez, obtienen el mayor valor de función de coste para el ángulo sólido que corresponde con el primer sector (lo que se conoce como criterio de reciprocidad), ambos sectores se consideran como intercambiados entre sí. Este criterio de reciprocidad también se extiende a casos en los que se tres sectores tienen sus azimuts rotados.

La segunda metodología (referida como Método II) propuesta en esta publicación presenta un conjunto de ecuaciones destinadas a calcular el azimut real de un sector. Estas ecuaciones se basan también en el número de traspasos realizados entre sector origen y destino, así como en la distancia entre ellos. Al igual que en el primer método, este segundo método posee un criterio de reciprocidad que permite identificar tanto pares como tríos de sectores intercambiados. En este caso, el criterio de reciprocidad consiste en encontrar sectores cuyo azimut computado se encuentra más cerca del azimut esperado para un sector colocalizado que para el suyo mismo, y viceversa.

Finalmente, se ha realizado un número relevante de simulaciones donde el Método I presenta el menor número de falsos positivos mientras que el Método II consigue la mejor tasa de verdaderos positivos en la detección de sectores intercambiados. Además, ambos métodos han sido evaluados en redes LTE comerciales mostrando resultados alineados con las simulaciones ejecutadas previamente. Por consiguiente, las metodologías propuestas han resultado ser la mejor alternativa a la realización de DT.

A.2.4 Detección de sectores intercambiados en redes multi-capa [IV] (Capítulo 6.2)

Al igual que la publicación anterior, esta publicación persigue el objetivo de diseñar un sistema que permita la detección de sectores intercambiados en redes de comunicaciones móviles (Objetivo 4). La principal diferencia con la anterior publicación es que este método sólo se puede aplicar en redes multi-capa. Esta publicación propone una metodología capaz de detectar sectores intercambiados usando estadísticas de movilidad entre celdas pertenecientes al mismo emplazamiento y en diferentes capas de frecuencias.

La metodología presentada en esta publicación se apoya en la premisa de que los traspasos desde una celda en una capa de frecuencia hacia celdas colocalizadas en una capa de frecuencia diferente son más probables de ser realizados hacia la celda colocalizada con cuyo azimut es más parecido al de la celda origen. Esta publicación también presenta un criterio de reciprocidad para identificar pares y tríos de sectores intercambiados a través de la metodología propuesta.

Finalmente, los resultados de este método se han comparado con los resultados obtenidos mediante los métodos propuestos en la publicación anterior, demostrando que se consigue mejorar la tasa de verdaderos positivos mientras que la de falsos positivos se mantiene similar.

A.2.5 Detección de sectores intercambiados en base a la localización del usuario durante traspasos entre emplazamientos [V] (Capítulo 6.3)

Esta publicación también pertenece al grupo de técnicas de auto-curación y, en concreto, a la detección de sectores intercambiados en redes de comunicaciones móviles. Sin embargo, esta publicación también persigue el diseño de una técnica de posicionamiento de subscriptores basada en funcionalidad estándar disponible por defecto en redes comerciales (Objetivo 5). Para ello, se usa información extraída de los mensajes de señalización enviados entre la red y el subscriptor. En particular, se usan mensajes de *Timing Advance* (TA) y *Measurement Report* (MR). TA es el procedimiento mediante el cual la red le indica al subscriptor que transmita datos con anticipación, de forma que estos lleguen a la estación base en el momento que les corresponde. Estos mensajes de TA pueden ser convertidos en distancias utilizando la velocidad de campos electromagnéticos en un medio dado. Los mensajes MR son enviados por los subscriptores a la red para notificarle a ésta que las condiciones RF han cambiado de forma que se podrían ejecutar procedimientos de movilidad. Estos mensajes MR incluyen las celdas que han sido medidas y los niveles de señal de éstas. Por tanto, cuando se inicia un traspaso por condiciones RF, al menos un mensaje MR ha debido ser enviado por el subscriptor con anterioridad. Esta publicación propone una técnica de posicionamiento de subscriptores que utiliza mensajes de TA enviados antes y después de que se realice un traspaso de forma que se pueda calcular la distancia entre el subscriptor y las celdas origen y destino del traspaso. Estas dos distancias se pueden representar como circunferencias rodeando las estaciones base a las cuales pertenecen las celdas origen y destino. Por tanto, cuando las celdas origen y destino pertenecen a distintas estaciones base, estas dos circunferencias intersecan en dos puntos. Como el subscriptor podría encontrarse en cualquiera de estos dos puntos, se utilizan los mensajes MR para decidir cuál de los dos puntos es la verdadera localización del subscriptor. Así, se selecciona como localización del subscriptor el punto de intersección más cercano al centro geométrico calculado mediante todas las celdas que aparecen en el mensaje MR.

La precisión de esta técnica de posicionamiento ha sido evaluada y comparada con otras técnicas del estado del arte usando datos de una red comercial LTE. Los resultados demuestran que la técnica propuesta es la más precisa de todas.

Además, esta publicación propone combinar esta técnica de posicionamiento con los métodos de detección de sectores intercambiados propuestos en las publicaciones anteriores con el objetivo de mejorar sus tasas de éxito (Objetivo 6). En concreto, se usa la posición del subscriptor como la localización en la que se efectúa el traspaso en lugar de usar la posición de la celda destino. Este método ha sido evaluado y ha demostrado que consigue mejores resultados que las metodologías del estado del arte tanto en términos de verdaderos positivos como de falsos positivos.

A.2.6 Detección de sectores borde en redes de Comunicaciones móviles [VI] (Capítulo 6.4)

Al igual que todas las publicaciones del capítulo 6, esta publicación está relacionada con técnicas de auto-curación. En particular, esta publicación surge de la necesidad de reducir el número de falsos positivos en métodos de detección de sectores intercambiados en redes de comunicaciones móviles (Objetivo 7).

Las diferentes metodologías propuestas por publicaciones relacionadas con la detección de sectores intercambiados pueden ser susceptibles a identificar como sectores intercambiados aquellos que en realidad no lo están pero que, debido a que se encuentran en zonas del borde de la red (sectores que dan servicio a montañas, lagos o mares), podrían causar que los algoritmos de detección fallen. Por tanto, es útil identificar sectores que pertenecen a estas zonas de forma que se le pueda aplicar un criterio de confianza a los resultados de las técnicas de detección de sectores intercambiados.

Así, esta publicación persigue detectar sectores que pertenecen a los límites de la red. Para ello, se proponen tres fases. La primera fase utiliza algoritmos de división en grupos para identificar áreas inconexas de la red, de forma que se reduzca la complejidad del problema de detección de sectores borde. La segunda fase presenta un algoritmo parametrizable diseñado para encontrar los nodos que conforman los contornos de las áreas identificadas en la primera fase. Finalmente, la última fase detecta cuáles de los sectores que forman parte de los nodos del contorno, están apuntando hacia el exterior de la red y, por tanto, pueden ser considerados como sectores borde.

La solución propuesta por esta publicación puede ser utilizada por todo tipo problemas en los que la detección de estaciones base o de sectores que se encuentran en los límites de una red de comunicaciones móviles sea útil. Así, se han realizado simulaciones para evaluar la bondad de la metodología propuesta como detector de celdas que poseen peor precisión en técnicas de geolocalización. Los resultados han corroborado la validez del método propuesto.

A.2.7 Ericsson Network Design and Optimization portfolio enhancement

Todas las publicaciones anteriores han sido integradas como parte del porfolio del grupo *Network Design and Optimization* de Ericsson, el cuál proporciona soluciones que facilitan a los operadores la automatización en la gestión de sus redes.

Concretamente, las técnicas descritas en los capítulos 4 y 5 han sido incorpordas a la herramienta *Ericsson Cell and Frequency Optimizer* y los métodos descritos en las publicaciones del capítulo 6 han sido incorporados como parte de la herramienta *Ericsson RAN Analyzer* y de la plataforma *Ericsson Cognitive Software*.

Por tanto, las técnicas, métodos y algoritmos desarrollados en esta tesis están siendo usados industrialmente con el objetivo de proporcionar soluciones a problemas reales en redes comerciales de comunicaciones móviles a la vez que permiten a los operadores reducir costes a través de la automatización de servicios.

A.3 Conclusiones

Esta tesis tiene como finalidad proporcionar soluciones a los problemas existentes en el área de SON. En especial, se ha identificado una serie de retos en los tres principales bloques en que se divide SON y se ha definido un total de ocho objetivos a perseguir para superarlos. Dos de estos objetivos están relacionados con el concepto de auto-configuración (Objetivo 1 y 2), uno lo está con el concepto de auto-optimización (Objetivo 3), cuatro lo están con el concepto de auto-curación (Objetivo 4, 5, 6 y 7) y, por último, un objetivo para implementar las soluciones propuestas en esta tesis en herramientas comerciales. De aquí en adelante, se presentan todas las contribuciones relacionadas con estos objetivos.

- **Objetivo 1**. Búsqueda de la localización óptima de estaciones base y CPE.
  - Se ha propuesto una nueva función de coste para planificar redes 5G FWA. En la función de coste clásica para redes FWA, todas las localizaciones en las que se puede instalar la antena del CPE contribuyen a la función de coste. Sin embargo, al contrario que en la función de coste clásica, la función propuesta considera todas estas localizaciones como candidatas de forma que aquella localización que minimice la función de coste será seleccionada como la localización en la que instalar la antena del CPE de forma que se maximice el rendimiento de la red.
  - Se ha realizado un ejercicio usando datos reales de un entono suburbano de forma que la función de coste propuesta para redes FWA pudiese ser evaluada. Para ello, se han calibrado modelos de propagación RF teóricos para la banda n257 [56] de 5G usando datos extraídos de DT. El objetivo de este ejercicio es el de encontrar las mejores localizaciones en las que desplegar los equipos de red de forma que se maximice el conjunto de KPIs de cobertura, dominancia y capacidad en la red 5G FWA.
  - Además, la función de coste propuesta para redes FWA se ha comparado con la función de coste clásica. Como resultado de esta comparativa, la función de coste propuesta para redes FWA ha superado los resultados

obtenidos con la función de coste clásica en dos ámbitos: el número de estaciones base a desplegar ha sido reducido y el valor final de los KPIs se ha visto mejorado.

- **Objetivo 2**. Encontrar una metodología que mejore aquellas del estado del arte en la selección de la configuración de los parámetros de antena tales como el azimut, tilt eléctrico o tilt mecánico para así maximizar el rendimiento en redes 5G FWA.
  - A diferencia de otras metodologías de diseño en las que las fases de planificación y configuración de la red se ejecutan una tras la otra de forma independiente, se ha propuesto una metodología iterativa que combina ambas fases.
  - Al igual que para el objetivo 1, se ha realizado un ejercicio usando datos de un entorno suburbano real con el propósito de evaluar la metodología iterativa propuesta. De nuevo, se han usado los mismos modelos de propagación RF para la banda n257 calibrados usando medidas tomadas de DT. Este ejercicio persigue encontrar las mejores configuraciones de azimut en una red 5G FWA de forma que los KPIs de cobertura, dominancia y capacidad sean óptimos.
  - Los resultados obtenidos tras este ejercicio se han comparado contra otras metodologías del estado del arte. La comparativa ha probado que la metodología propuesta alcanza mejores métricas en los KPIs mientras que el número de estaciones base necesarias se ha reducido.
  - La metodología propuesta puede ser ejecutada continuamente de forma que la red pueda adaptarse a los cambios que sufra el entorno RF.
  - Además, esta metodología iterativa puede ser utilizada por cualquier actividad de diseño de redes de comunicaciones móviles.
- **Objetivo 3**. Calibración de modelos de propagación RF a través de funcionalidad estandarizada.
  - Se ha propuesto una metodología que permite la caracterización de la huella de propagación RF en redes LTE y 5G. Esta metodología se basa

en información estandarizada de configuración y rendimiento de la red que permite a los operadores prescindir de la ejecución de DT.

- Esta metodología genera distribuciones de señal por celda y distribuciones de interferencia por par de celdas de forma que puedan ser usadas con la finalidad de calibrar modelos teóricos de propagación RF en redes LTE y 5G de forma que éstos describan la realidad de forma más precisa.
- La metodología propuesta utiliza distribuciones gaussianas como modelo representativo de distribución.
- La metodología propuesta utiliza estadísticas generadas a través del comportamiento de los subscriptores de la red. Por tanto, el modelo generado es más completo que aquel construído a través de DT, ya que se consideran zonas en las que se encuentran los subscriptores (edificios, calles peatonales, etc.) y dónde los DT no son capaces de realizar medidas. Por consiguiente, el modelo generado por esta metodología es más representativo que el generado por DT ya que sólo se tienen en cuenta las localizaciones reales en que se encuentran los subscriptores.
- El método propuesto se puede implementar o bien como parte de la OSS siendo un algoritmo de SON centralizado o como parte de las estaciones base actuando como un algoritmo de SON distribuido.

- **Objetivo 4**. Sistema de detección de sectores intercambiados basado en estadísticas de movilidad.

  - Se ha diseñado un sistema que usa información de configuración de la red (la localización de las celdas, el azimut esperado de las antenas y el ancho de haz de las antenas) e información de rendimiento de la red (estadísticas de movilidad tales como el número de traspasos por relación de celdas) para detectar sectores intercambiados en redes LTE y 5G.
  - El sistema propuesto se divide en dos técnicas: una técnica basada en movilidad entre emplazamientos y una técnica basada en la movilidad dentro de un emplazamiento. La primera de estas técnicas utiliza la localización de las celdas y sus vecinas para encontrar una dirección media

en la que se puede encontrar a los subscriptores en base a sus patrones de movilidad. A continuación, esta dirección es comparada con el azimut esperado de la antena del sector con la intención de encontrar grandes desviaciones. La segunda técnica de este sistema utiliza movilidad entre diferentes capas de frecuencia dentro del mismo emplazamiento para encontrar patrones de movilidad inesperados que pudieran indicar que el azimut de la antena de un sector no está apuntando hacia la dirección esperada.

- Además, se ha añadido al sistema un criterio basado en la necesidad de encontrar un segundo o tercer sector con grandes desviaciones de azimut de forma que éstos hayan podido ser intercambiados.
- Para validar este sistema se han utilizado dos simuladores. Así, se han ejecutado más de un millón de simulaciones utilizando configuraciones de red diferentes para eliminar cualquier sesgo debido a la configuración de la red o a los patrones de movilidad de los usuarios. Las simulaciones han sido configuradas de forma que se fuercen sectores intercambiados. Finalmente, se han extraído las estadísticas de movilidad de estas simulaciones de forma que éstas puedan ser utilizadas por el sistema propuesto.
- Se han utilizado dos indicadores para evaluar el sistema propuesto: la tasa de verdaderos positivos (es decir, el número de casos correctamente identificados dividido entre el número total de casos) y la tasa de falsos positivos (es decir, el número de casos detectados de forma errónea dividido entre el número total de posibles casos en la red). En base a estos indicadores, se ha probado que el sistema propuesto mejora las metodologías del estado del arte.
- La técnica basada en movilidad dentro del mismo emplazamiento ha mostrado los mejores resultados. Sin embargo, ésta sólo puede ser utilizada en emplazamientos que poseen al menos dos capas de frecuencias diferentes. Por el contrario, la técnica basada en movilidad entre distintos emplazamientos puede ser usada independientemente del número de capas de frecuencia.

   - Además, se ha evaluado el método propuesto usando datos de redes de LTE comerciales. Como DT es la metodología estandarizada para la detección de sectores intercambiados, se han realizado actividades de DT con el objetivo de probar la validez del sistema propuesto como remplazo de éstos. Estas actividades han confirmado que los casos propuestos por el sistema se tratan de casos de sectores intercambiados reales.

- **Objetivo 5**. Diseño de una técnica de posicionamiento de subscriptores en redes LTE y 5G con mayor precisión que los métodos actuales basados en funcionalidad estándar.

   - Se ha propuesto un estimador de la posición de los subscriptores basado en técnicas de tiempo de llegada. Este estimador combina información extraída de mensajes de TA y MR estandarizada en redes LTE y 5G. Por tanto, es de aplicabilidad universal en estas redes.
   - Se han usado datos extraídos de una red comercial de LTE para validar el estimador propuesto. En particular, se ejecutaron WT para determinar la posición real de los subscriptores de esta prueba de validación. Se han usado los valores de *International Mobile Subscriber Identity* (IMSI) de los subscriptores que forman parte del WT con el propósito de encontrar sus mensajes entre todos los mensajes de señalización extraídos de la OSS.
   - Toda la información recolectada ha sido usada para determinar la precisión del estimador propuesto en el posicionamiento de los subscriptores. Esta precisión se ha comparado con la precisión de otras técnicas de posicionamiento del estado del arte, resultando el estimador propuesto como la mejor técnica de posicionamiento.

- **Objetivo 6**. Combinar el Objetivo 4 y el Objetivo 5 para mejorar la tasa de éxito de las técnicas de detección de sectores intercambiados.

   - Técnicas de posicionamiento de subscriptores se han usado para mejorar la metodología propuesta en el Objetivo 4 basada en movilidad entre distintos emplazamientos. Inicialmente, esta metodología usaba la localización de la celda destino del traspaso como la posición en la que se realizaba el mecanismo de traspaso. Sin embargo, ahora se propone utilizar técnicas de posicionamiento de subscriptores para estimar la posición real en la que se realiza el traspaso.

- ○ Estadísticas de movilidad de una red comercial se han modificado con la intención de simular la existencia de sectores intercambiados. A continuación, se han utilizado diferentes técnicas de posicionamiento de subscriptores para determinar las localizaciones en las que se han efectuado los traspasos. De esta forma, se ha mejorado la metodología de detección de sectores intercambiados.
- ○ La resultados han concluido que la utilización de técnicas de posicionamiento para identificar la localización real en la que se realiza el traspaso mejora tanto la tasa de verdaderos positivos como la de falsos positivos en la metodología de detección de sectores intercambiados basada en la movilidad entre distintos emplazamientos.

- **Objetivo 7**. Encontrar una metodología capaz de reducir el número de falsos positivos en la detección de sectores intercambiados.
  - ○ Se ha propuesto una metodología cuya finalidad es identificar sectores borde de una red de comunicaciones móviles. Esto es, una metodología que identifique aquellas celdas que se encuentran en los límites de la red y cuyas antenas están apuntando hacia fuera del núcleo de la red.
  - ○ Se ha realizado un conjunto de simulaciones para evaluar la metodología propuesta. En particular, se ha usado como punto de referencia la técnica de posicionamiento *Received Signal Strength* (RSS), que presenta peor precisión cuando los subscriptores son servidos por sectores borde. Las simulaciones han probado de forma exitosa que el método propuesto identifica de forma apropiada los sectores borde ya que los valores de precisión globales mejoran cuando estos sectores no son considerados.
  - ○ La metodología propuesta se puede aplicar a cualquier caso de uso que necesite identificar sectores borde. Por tanto, como la metodología de detección de sectores intercambiados basada en estadísticas de movilidad entre diferentes emplazamientos es propensa a fallar en los sectores

borde, donde la localización del traspaso puede ser estimada de forma incorrecta, esta metodología es útil para descartar estos sectores de entre todos los casos detectados. De esta forma, se puede reducir el número de falsos positivos.

- **Objetivo 8**. Implementar todos los métodos, técnicas y algoritmos desarrollados en esta tesis en herramientas comerciales de planificación, optimización y búsqueda de fallos.

    - El porfolio del grupo *Network Design and Optimization* de Ericsson ha sido aumentado con la adición de nuevos módulos que incorporan las funcionalidades estudiadas y propuestas en esta tesis. En concreto, las herramientas comerciales que ahora incluyen estas funcionalidades son *Ericsson RAN Analyzer*, *Ericsson Cell and Frequency Optimizer* y *Ericsson Cognitive Software*.

A.4 Resultados

Esta sección presenta las contribuciones y actividades derivadas de la elaboración de esta tesis.

A.4.1 Publicaciones en revistas

Esta tesis ha derivado en cinco publicaciones en revistas de alto impacto. Tabla A.1 lista estas publicaciones.

A.4.2 Conferencias

Tabla A.2 resume la lista de conferencias derivadas de ests tesis.

TABLA A.1: Publicaciones.

	Publicación	FI	Ranking de la revista
I	O. Kaddoura et al. "Greenfield Design in 5G FWA Networks" IEEE Communications Letters vol. 23, no. 12, pp. 2422-2426, Dec. 2019 doi: 10.1109/LCOMM.2019.2939470	3.419	Q2 (32/90) Telecommunications
II	O. Kaddoura, J. Outes, J. J. Sánchez-Sánchez and R. Barco "Radio Frequency Footprint Characterization Based on Mobility Indicators" IEEE Wireless Communications Letters Sep. 2020 doi: 10.1109/LWC.2020.3023283	4.660	Q1 (2019) (17/90) Telecommunications
III	O. Kaddoura, R. Barco, I. Serrano and J. J. Sánchez-Sánchez "Swapped Sectors Detection Based on Mobility Statistics" IEEE Communications Letters vol. 22, no. 5, pp. 1038-1041, May 2018 doi: 10.1109/LCOMM.2018.2808292	3.457	Q2 (28/88) Telecommunications
IV	O. Kaddoura, J. J. Sánchez-Sánchez, I. Serrano and R. Barco "Swapped Sectors Detection on Multi-Layer Networks" IEEE Communications Letters vol. 22, no. 11, pp. 2342-2345, Nov. 2018 doi: 10.1109/LCOMM.2018.2867846	3.457	Q2 (28/88) Telecommunications
V	O. Kaddoura, J. J. Sánchez-Sánchez, I. Serrano and R. Barco "Swapped Sectors Detection Based on User Location During Inter-Site Handovers" IEEE Access vol. 7, pp. 92547-92560, 2019 doi: 10.1109/ACCESS.2019.2927607	3.745	Q1 (61/266) Engineering, electrical & electronic

TABLA A.2: Conferencias.

	Conferencia
VI	O. Kaddoura, I. Serrano, J. J. Sánchez-Sánchez and R. Barco "Edge Sectors Detection in Mobile Communications Networks" 2019 European Conference on Networks and Communications (EuCNC), Valencia, Spain 2019, pp. 586-591 doi: 10.1109/EuCNC.2019.8801977
VII	O. Kaddoura, I. Serrano and R. Barco "Detección de sectores borde en redes de comunicaciones móviles" XXIV Simposium nacional de la Unión Científica Internacional de Radio, Valencia, 2014

A.4.3 Patentes

Tabla A.3 lista la patente derivada de la elaboración de esta tesis.

TABLA A.3: Patentes.

	Patente
VIII	O. Kaddoura, J. Outes and G. Payo "Method and Apparatus for Characterizing a Radio Frequency Environment in a Telecommunications Network" 03.10.2019 PCT/EP2018/057995

A.4.4 Colaboración con la industria

Esta tesis ha sido realizada en colaboración con el grupo *Network Design and Optimization* de Ericsson. Por tanto, todas las soluciones derivadas de esta tesis han sido implementadas como parte de herramientas comerciales tales como *Ericsson RAN Analyzer*, *Ericsson Cell and Frequency Optimizer* y *Ericsson Cognitive Software*.

A.4.5 Estancias de investigación

Como parte de esta tesis, se han realizado cuatro estancias en organismos de investigación internacionales. En particular, estas estancias se desarrollaron en instalaciones de Ericsson en Estados Unidos e India con una duración total de 92 días tal y como se detalla en Tabla A.4.

TABLA A.4: Estancias de investigación.

	Área de investigación	**Localización**	**Duración**
i	Optimización de Red Radio	Plano, Texas. U.S.A.	12/11/2014 - 04/12/2014 23 días
ii	Optimización de Red Radio	Irvine, California. U.S.A.	22/06/2015 - 03/07/2015 12 días
iii	Optimización de Red Radio	Irvine, California. U.S.A.	06/06/2016 - 24/06/2016 19 días
iv	IA en Sistemas Autónomos Inteligentes	Bengaluru. India	03/09/2019 - 10/10/2019 38 días

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