Universidad de Málaga

Escuela Técnica Superior de Ingeniería de Telecomunicación

Programa de Doctorado en Ingeniería de Telecomunicación

UNIVERSIDAD DE MÁLAGA

TESIS DOCTORAL

Detection and Compensation Methods for Self-Healing in Self-Organizing Networks

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2017

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EDITA: Publicaciones y Divulgación Científica. Universidad de Málaga

Por la presente, **Dra. Dª. Raquel Barco Moreno y Dr. D. Matías Toril Genovés**, profesores doctores del *Departamento de Ingeniería de Comunicaciones* de la Universidad de Málaga,

CERTIFICAN:

Que **Dª. Isabel de la Bandera Cascales**, Ingeniera de Telecomunicación, ha realizado en el Departamento de Ingeniería de Comunicaciones de la Universidad de Málaga bajo su dirección, el trabajo de investigación correspondiente a su TESIS DOCTORAL titulada:

"Detection and Compensation Methods for Self-Healing in Self-Organizing Networks"

En dicho trabajo se han propuesto aportaciones originales para la gestión de problemas en redes móviles. En particular, se han propuesto métodos para la detección y compensación de diferentes fallos. Además, se ha desarrollado una herramienta de simulación de la tecnología celular LTE para la evaluación de las técnicas propuestas. Los resultados expuestos han dado lugar a publicaciones en revistas, patentes y aportaciones a congresos.

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

En Málaga, a _______ de _____________ de _______

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Reunido el tribunal examinador en el día de la fecha, constituido por:

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para juzgar la Tesis Doctoral titulada *Detection and Compensation Methods for Self-Healing in Self-Organizing Networks* realizada por D^a. Isabel de la Bandera Cascales y dirigida por la Dra. D^a. Raquel Barco Moreno y el Dr. D. Matías Toril Genovés, acordó por

______________________________ otorgar la calificación de

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se extiende firmada por los componentes del tribunal la presente diligencia.

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A mis niños.

Acknowledgements

At last this day has come and I am close to finishing this stage. It has been a large and intense journey which would have been very different without all the people that I have met during these years.

Firstly, I would like to express my most sincere gratitude to my supervisors, Raquel and Matías. Many thanks to Raquel for giving me the opportunity to become part of this exceptional team, for being available at all times for any problem that I had, and for her support and affection during all these years. Many thanks to Matías for his guidance, for all the hours spent with the simulator and for his knowledge and encouragement that have helped me in each step.

I would also like to thank Salva, who introduced me to this amazing world of mobile communications for the first time.

I wish to thank all my office mates that have been with me during all these years. There is no doubt that with their support and sense of humor this work has been more pleasant. Special mention to Emil, David and Ana for all the discussions and good advice and for all the shared laughs. I would like to express my special thanks to Pablo. He is the only one who has been with me since the beginning and the main support. Thanks for his patience, for helping me make every decision, for sharing with me all his knowledge and for assisting me in writing papers. I know that this work is also yours.

I must also acknowledge the financial support given by the projects mentioned below, together with the research group TIC-102 Ingeniería de Comunicaciones and Universidad de Málaga. They made this work possible and allowed me to present results and exchange knowledge and skills in conferences and journals.

I would like to strongly thank my family for their love and support. Thanks to my parents for their motivation and trust during these years and all my life. I know that I would not have achieved many of my successes in life without them. Thanks to Cristina, my favorite sister. Her opinion is always the most important even if it is usually the opposite to mine. There is no doubt that I will always ask you for advice. And thanks to Javier for wanting to be part of this family.

I could not finish these lines without thanking my beautiful family. These years of intense work have also brought me the most important thing of all my life, my beautiful children. All of this work and everything else is for them. Thanks to my husband for his support, his motivation, his optimism, his love and for being by my side all the way. And thanks to God, who is there in every single step.

This thesis was partially funded by the following projects:

- P08-TIC-4052 grant from the Junta de Andalucía.
- 8.06/5.59.3721, contract with Optimi-Ericsson, with support from the Junta de Andalucía (Agencia IDEA, Consejería de Ciencia, Innovación y Empresa) and ERFD.
- 8.06/5.59.3722, contract with Optimi-Ericsson, with support from the Junta de Andalucía (Agencia IDEA, Consejería de Ciencia, Innovación y Empresa) and ERFD.
- P12-TIC-2905 grant from the Junta de Andalucía.

Contents

Abstract

One of the key elements of the 3rd Generation Partnership Project (3GPP) current standards of mobile communications, such as LTE (Long Term Evolution) and LTE-Advanced, is the consideration of automated features. Networks with those capabilities are known as Self-Organizing Networks (SON). SON aim to cope with the significant increase in size and complexity experienced by mobile networks in the last years. The number of users is increasingly high and services require higher data rates and a large amount of available radio resources. Consequently, network management has become a very complex task. Moreover, future 5th Generation (5G) networks will involve even much higher complexity and cost. In this context, SON functions will be required to cope with the management of such a complex network. The ultimate goal of SON is to define a set of functionalities that allow to automate network management. By automating network optimization and maintenance, it is possible to reduce operational expenditures (OPEX) and capital expenditures (CAPEX).

SON functionalities are grouped in three classes: Self-Configuration, Self-Optimization and Self-Healing. The aim of Self-Configuration functions is to automatically define the configuration parameters of every new equipment in the planning or the deployment phase. Self-Optimization functions automatically modify network parameters during the operational phase to improve network performance by adapting the network to changes of environment conditions. Self-Healing functions allow to detect and diagnose performance failures in the network without human intervention. When a failure is detected in a cell, it can be recovered (recovery function) or compensated (compensation function).

One of the main challenges related to SON is the development of effective methods for the automation of the optimization and maintenance tasks. In this sense, research efforts have been focused on the development of methods for Self-Configuration and Self-Optimization, whereas Self-Healing functions have been less addressed. For that reason, it is not easy to find really efficient detection and compensation algorithms for mobile networks in the literature. Many studies present detection and compensation algorithms that provide good results but with the drawback of a high complexity. In addition, in many cases, a specific detection or compensation algorithm can be presented as a global solution for multiple types of degradation, thus compromising their effectiveness.

Furthermore, a significant effort has been devoted to the search for SON solutions based

on analytical and simulated models. However, the main challenges are now linked to devising SON solutions which are based on data from live networks. This is particularly interesting in the area of Self-Healing. In this context, the availability of historical data is crucial to understand how the network behaves under normal and faulty conditions or how the faults impact on the Quality-of-Experience.

The main goal of this thesis is to develop effective detection and compensation algorithms for mobile networks. Firstly, a Cell Outage Detection (COD) algorithm based on handover statistics is proposed. In spite of its simplicity, the proposed algorithm allows to detect cell outages in any network immediately after collecting network performance indicators. Secondly, a novel Cell Outage Compensation (COC) methodology is proposed. The conceived method adapts the compensation action to the specific degradation produced by the cell outage. Once the cell outage is detected, an analysis is carried out to find out the degradation caused in the neighboring cells. Afterwards, different COC algorithms can be applied to each neighboring cell depending on the kind of degradation.

Thirdly, state-of-the-art proposes compensation solutions for cell outages. Conversely, in this thesis a cell problem different to an outage is analyzed: a weak coverage problem. Specifically, a Cell Degradation Compensation (CDC) algorithm based on handover margin modifications is proposed.

Many of the methods proposed in this thesis have been designed and validate based on real networks data. Unfortunately, although it is interesting to evaluate the proposed methods in live networks, this is not always possible. Operators are sometimes unwilling to test algorithms in live networks, especially when test needs changing configuration parameters. For this reason, part of this thesis is dedicated to the implementation of a dynamic system-level simulator that allows the evaluation of the proposed algorithms.

Resumen

Uno de los elementos clave en la definición de los recientes estándares de comunicaciones móviles del *3rd Generation Partnership Project* (3GPP), LTE (*Long Term Evolution*) y LTE-*Advanced*, es la consideración de funciones que se puedan ejecutar de manera automática. Este tipo de redes se conocen como redes Auto-Organizadas (*Self-Organizing Networks*, SON). Las funciones SON permiten hacer frente al importante incremento en tamaño y complejidad que han experimentado las redes de comunicaciones móviles en los últimos años. El número de usuarios es cada vez mayor y los servicios requieren gran cantidad de recursos y altas tasas de transmisión por lo que la gestión de estas redes se está convirtiendo en una tarea cada vez más compleja. Además, cuando las redes de quinta generación (5G) se implanten, la complejidad y el coste asociado a estas nuevas redes será todavía mayor. En este contexto, las funciones SON resultan imprescindibles para llevar a cabo la gestión de estas redes tan complejas. El objetivo de SON es definir un conjunto de funcionalidades que permitan automatizar la gestión de las redes móviles. Mediante la automatización de las tareas de gestión y optimización es posible reducir los gastos de operación y capital (OPEX y CAPEX).

Las funciones SON se clasifican en tres grupos: Auto- Configuración, Auto-Optimización y Auto-Curación. Las funciones de Auto-Configuración tienen como objetivo la definición de los distintos parámetros de configuración durante la fase de planificación de una red o después de la introducción de un nuevo elemento en una red ya desplegada. Las funciones de Auto-Optimización pretenden modificar los parámetros de configuración de una red para maximizar el rendimiento de la misma y adaptarse a distintos escenarios. Las funciones de Auto-Curación tienen como objetivo detectar y diagnosticar posibles fallos en la red que afecten al funcionamiento de la misma de manera automática. Cuando un fallo es detectado en una celda este puede ser recuperado (función de recuperación) o compensado (función de compensación).

Uno de los principales desafíos relacionado con las funciones SON es el desarrollo de métodos eficientes para la automatización de las tareas de optimización y mantenimiento de una red móvil. En este sentido, la comunidad científica ha centrado su interés en la definición de métodos de Auto-Configuración y Auto-Optimización siendo las funciones de Auto-Curación las menos exploradas. Por esta razón, no es fácil encontrar algoritmos de detección y compensación realmente eficientes. Muchos estudios presentan métodos de detección y compensación que producen buenos resultados pero a costa de una gran complejidad. Además, en muchos casos, los algoritmos de detección y compensación se presentan como solución general para distintos tipos

de fallo lo que hace que disminuya la efectividad.

Por otro lado, la investigación ha estado tradicionalmente enfocada a la búsqueda de soluciones SON basadas en modelos analíticos o simulados. Sin embargo, el principal desafío ahora está relacionado con la explotación de datos reales disponibles con el objetivo de crear una base del conocimiento útil que maximice el funcionamiento de las actuales soluciones SON. Esto es especialmente interesante en el área de las funciones de Auto-Curación. En este contexto, la disponibilidad de un histórico de datos es crucial para entender cómo funciona la red en condiciones normales o cuando se producen fallos y como estos fallos afectan a la calidad de servicio experimentada por los usuarios.

El principal objetivo de esta tesis es el desarrollo de algoritmos eficientes de detección y compensación de fallos en redes móviles. En primer lugar, se propone un método de detección de celdas caídas basado en estadísticas de traspasos. Una de las principales características de este algoritmo es que su simplicidad permite detectar celdas caídas en cualquier red inmediatamente después de acceder a los indicadores de funcionamiento de la misma. En segundo lugar, una parte importante de la tesis está centrada en la función de compensación. Por un lado, se propone una novedosa metodología de compensación de celdas caídas. Este nuevo método permite adaptar la compensación a la degradación específica provocada por la celda caída. Una vez que se detecta un problema de celda caída, se realiza un análisis de la degradación producida por este fallo en las celdas vecinas. A continuación, diferentes algoritmos de compensación se aplican a las distintas celdas vecinas en función del tipo de degradación detectado. En esta tesis se ha llevado a cabo un estudio de esta fase de análisis utilizando datos de una red real actualmente en uso.

Por otro lado, en esta tesis también se propone un método de compensación que considera un fallo diferente al de celda caída. En concreto, se propone un método de compensación para un fallo de cobertura débil basado en modificaciones del margen de traspaso.

Por último, aunque es interesante evaluar los métodos propuestos en redes reales, no siempre es posible. Los operadores suelen ser reacios a probar métodos que impliquen cambios en los parámetros de configuración de los elementos de la red. Por esta razón, una parte de esta tesis ha estado centrada en la implementación de un simulador dinámico de nivel de sistema que permita la evaluación de los métodos propuestos.

Acronyms

3G	3rd Generation
3GPP	3rd Generation Partnership Project
5G	5th Generation
AM	Acknowledge Mode
AMC	Adaptive Modulation and Coding
ARQ	Automatic Repeat Request
AS	Access Stratum
AWGN	Additive White Gaussian Noise
BC	Best Channel
BLER	Block Error Rate
CAPEX	Capital Expenditures
CBR	Call Blocking Ratio
CCO	Capacity and Coverage Optimization
CDC	Cell Degradation Compensation
CDD	Cell Degradation Detection
CDMA	Code-Division Multiple Access

CDR	Call Dropping Ratio
CM	Configuration Management Parameters
CMC	Connection Mobility Control
COC	Cell Outage Compensation
COD	Cell Outage Detection
COM	Cell Outage Management
CPU	Computer Processing Unit
CQI	Channel Quality Indicator
eNB	evolved Node B
EPA	Extended Pedestrian A
EPC	Evolved Packet Core
EPS	Evolved Packet System
ETU	Extended Typical Urban
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
EVA	Extended Vehicular A
FLC	Fuzzy Logic Controller
GSM	Global System for Mobile communications
GPRS	General Packet Radio Service
HARQ	Hybrid Automatic Repeat Request
HO	Handover
HOH	Handover Hysteresis
HOM	Handover Margin
HOSR	Handover Success Rate

HPR	HO ping-pong Ratio
inHO	incoming HO
KPI	Key Performance Indicators
LDF	Large Delay First
LTE	Long-Term Evolution
MAC	Medium Access Control
MBMS	Multimedia Broadcast Multicast Service
MCS	Modulation and Coding Scheme
MIMO	Multiple-Input Multiple-Output
MME	Mobility Management Entity
NAS	Non-Access Stratum
NGMN	Next Generation Mobile Networks
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiplex Access
OPEX	Operational Expenditures
OSS	Operations Support System
PDCP	Packet Data Convergence Control
PDSCH	Physical Downlink Shared Channel
PDU	Packet Data Unit
PF	Proportional Fair
PM	Performance Management Parameter
PRB	Physical Resource Block
P-GW	Packet Data Network Gateway

QAM	Quadrature Amplitude Modulation
QoS	Quality-of-Service
QPSK	Quadrature Phase Shift Keying
RAC	Radio Admission Control
RACH	Random Access Channel
RAT	Ratio Access Technology
RBC	Radio Bearer Control
RE	Resource Element
RLC	Radio Link Control
RR	Round Robin
RRC	Radio Resource Control
RRM	Radio Resource Management
RS	Reference Signal
RSRP	Reference Signal Receive Power
RSRQ	Reference Signal Receive Quality
RSSI	Received Signal Strength Indicator
SC-FDMA	Single Carrier Frequency Division Multiple Access
SDU	Service Data Unit
S-GW	Serving Gateway
SINR	Signal to Interference plus Noise Ratio
SISO	Single Input Single Output
SON	Self-Organizing Networks
TB	Transport Block

TTI	Transmission Time Interval
TTT	Time-To-Trigger
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
US	Uncorrelated Scattering
VoIP	Voice over IP
WLAN	Wireless Local Area Network
WSS	Wide-Sense Stationary
WSSUS	Wide-Sense Stationary Uncorrelated Scattering

Chapter 1

Introduction

This first chapter introduces the main topics of this thesis, presenting the motivation, the objectives and the document structure.

1.1 Motivation

During the last decades, the mobile communications industry has experienced a significant increase, leading to a constant evolution of the related technologies. At the same time, the number of users demanding mobile services has experienced an exponential increase, as 95% of the global population live in an area that is covered by a mobile cellular network [1]. Thus, the mobile terminals (e.g., smartphones) have become an essential element for most people, which use them in different areas of life, not only as a basic instrument in their jobs, but also for fun. This fact has lead to a growing complexity and variety of the demanded services.

To cope with the large number of users and the complexity of existing services, the developed technologies have had to evolve quickly. The first digital networks (i.e., Global System for Mobile communications, GSM) provided a voice service of high quality and led to the first important expansion of the mobile networks. However, users were soon demanding other types of services and these networks resulted insufficient to satisfy the growing demand. Thus, the 3rd generation (3G) of mobile communications (e.g., Universal Mobile Telecommunications System, UMTS) appeared. This standard, developed by the 3G Partnership Project (3GPP) group, offered data services in addition to the voice service. The 3G networks continued evolving in order to improve network performance and to offer more complex services. Currently, a new standard (i.e., Long Term Evolution, LTE) is being deployed to cope with the enormous demand of services. The key benefits of LTE can be summarized in improved system performance, higher data rates and spectral efficiency, reduced latency and power consumption, enhanced flexibility of spectral usage and simplified network architecture [2].

In such a scenario, network operators have two main objectives: to satisfy the large traffic demand, while keeping capital expenditures (CAPEX) and operational expenditures (OPEX) at minimum values. The most effective way to achieve this objective is to automate network management tasks. This is the main purpose of Self-Organizing Networks (SON) [3]. SON concept was first published in 2008 by the Next Generation Mobile Networks (NGMN) Alliance [4, 5]. Later, the 3GPP also included SON as an important element of the new standard of mobile communications, LTE. Moreover, the complexity and cost of future 5th Generation (5G) mobile networks will be even higher, thus SON functionalities will be essential [6, 7]. To solve these issues, the 3GPP defines different SON functionalities and groups them into three categories [3]: Self-Configuration, Self-Optimization and Self-Healing. Self-Configuration [8] functions aim to automatically define the configuration parameters of the network elements in the planning phase or when a new equipment is added to an existing infrastructure. The objective of the Self-Optimization [8] functions is to modify network parameters, adapting the network to different environment conditions without human intervention. Finally, Self-Healing [9, 10] functions aim to cope with network faults that worsen user performance. In particular, the Self-Healing functions (Fig. 1.1) include the collection of information about the network performance, the detection and diagnosis of faults and the compensation or recovery actions to mitigate or solve the problem.

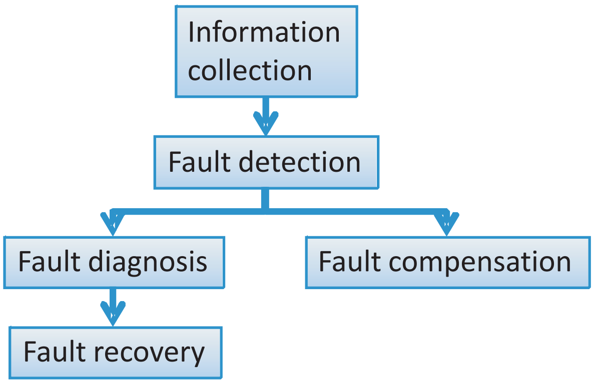

Figure 1.1: Self-Healing functions [10].

In addition to network operators, the research community has also shown a considerable interest in SON functions. Thus, in the last years, many international research projects have focused on optimization and management tasks in mobile networks. Some of these projects are CELTIC Gandalf [11], E3 [12], SOCRATES [13], SELF-NET [14], UniverSelf [15], SEMAFOUR [16] and COMMUNE [17]. Most of these projects are focused on Self-Configuration and Self-Optimization, whereas Self-Healing have received less attention. In addition, not all the Self-Healing functions are considered with the same interest. Specifically, there are many works that present algorithms in charge of the detection of failures in the network [18, 19, 20, 21, 22, 23, 24, 25, 26]. In most cases, the detection is carried out by analyzing the network behavior and comparing it with the normal performance. One of the possible failures that can appear in a network is a cell outage. A cell is in outage when it cannot carry traffic due to a failure. Several works about Cell Outage Detection (COD) can be found in the literature [27, 28, 29, 30, 31, 32]. Most of these works are based on the analysis of the performance of the problematic cell or its neighboring cells. With this methodology, only the most severe cases can be detected but many other outage situations may go unnoticed. Some approaches [30] can detect most cases of cell outage, but at the expense of a high complexity.

In addition to the COD use case, the 3GPP defines another important use case in Self-Healing, namely Cell Outage Compensation (COC) [9]. COC aims to reduce the degradation caused by a failure in a cell until the fault is solved. The compensation can be made by modifying different configuration parameters in the network. These parameters are usually from neighboring cells. All the modifications carried out by the compensation algorithm must be reverted when the network failure is solved. Several COC algorithms have been proposed in the literature [33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45]. In these works, the authors present different algorithms based on the modification of one or more control parameters and using different techniques (e.g., Fuzzy Logic, Reinforcement Learning). In all of them, the main objective is to reduce the degradation produce by the cell outage. However, these approaches present two important limitations. On the one hand, all previous works assume that the main effect produced by the cell outage is a coverage hole. Thus, the main objective of these algorithms is to cover the outage area by increasing the coverage area of the neighboring cells. However, the effects caused by an outage problem depend on the type of scenario and the network conditions. For instance, in a network with a high level of overlapping between cells, a cell outage problem may not result in a coverage hole. In this network condition, a cell outage might produce mobility problems between the neighboring cells or overload problems if the amount of traffic absorbed by the neighboring cells is excessive. Furthermore, in these scenarios, a cell outage may produce different effects in different neighboring cells at the same time. Therefore, when an outage problem does not produce a coverage hole and the degradation observed in the neighboring cells is not related to a lack of coverage, state-of-the-art COC methods may be ineffective.

On the other hand, in all these works, the different algorithms have been applied to the same network failure, i.e., a cell outage. However, there are many other network failures that can occur and affect the network performance [46]. These other faults (e.g., cell overshooting, weak coverage, etc.) may cause an important degradation in the network so that a compensation method is needed while the fault is identified and repaired. In these cases, the faulty cell is still active and that allows to consider the modification of its own parameters, and not only neighboring cells' parameters, as part of the compensation method.

Consequently, given the limitations of current state-of-the-art explained above, this thesis is focused on improving the detection and compensation of the cell outage problem and expand the compensation function to other failures.

1.2 Research objectives

The main goal of this thesis is the design and development of algorithms for the detection and compensation of failures in a mobile network. For this purpose, this thesis addresses two important phases of the Self-Healing process, namely problem detection and compensation.

Fig. 1.2 presents the different stages of a typical Self-Healing system. When a failure occurs in a network, the first phase is the fault detection. Once the fault has been detected, the compensation algorithm tries to mitigate the caused degradation until the fault is identified and solved. At that moment, the changes made by the compensation algorithm must be reverted. This thesis deals with the detection and compensation phases. Fig. 1.2 also presents the objectives of this thesis (yellow boxes).

To achieve the main goal, several research lines have been addressed:

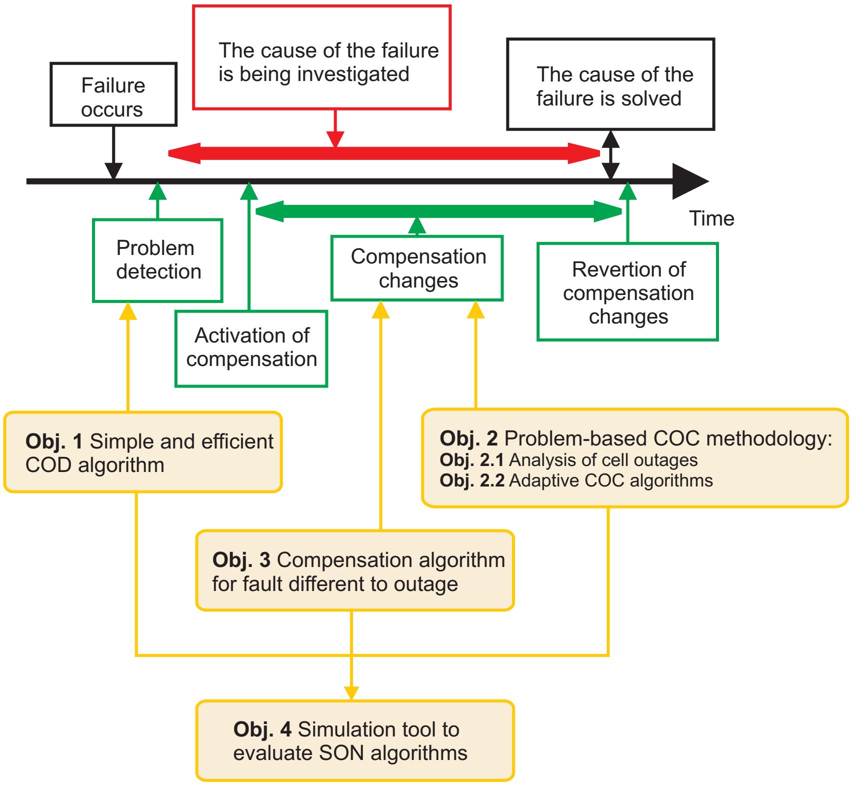

Figure 1.2: Time diagram of the Self-Healing process and thesis objectives.

Obj.1 *Design of a COD algorithm.* The first objective is to design a COD algorithm which improves the detection rate of state-of-the-art algorithms, at the same time being simple.

Obj.2 *Design of a novel COC methodology.* Once the cell outage is detected, the second objective is to propose a novel COC methodology. This novel methodology is based on the idea of addressing each neighboring cell of a cell in outage as an independent case, as opposed to the state-of-the-art approach of not considering the different effects of the outage on neighbors. It is based on the fact that cell outages can impact on each neighboring cell in a different way. For instance, in some cases, a cell outage could lead to mobility issues in neighboring cells due to a lack of a dominant cell, whereas in other cases the cell outage may produce a coverage hole. This method consists of two phases:

Obj.2.1 *Analysis of the degradation caused by the cell outage.* The analysis should be made by measuring the relation between Key Performance Indicators (KPIs) in order to extract valuable information from a vast amount of data. In addition, an estimation of the amount of traffic that is potentially lost as a consequence of cell outages should be considered. This is important since lost traffic can result in a potential loss of market share and revenues for the service provider.

Obj.2.2 *Design of adaptive COC algorithms.* From the previous analysis, it will be possible to select the set of cells that should take part in the compensation action and the control parameters to be modified on a cell basis. Thus, the COC function will be adapted to the specific problem detected in the neighboring cells.

Obj.3 *Design of a novel Cell Degradation Compensation (CDC) algorithm.* The third objective is to design a CDC algorithm for a fault different to a cell outage. Although the COC function has been extensively studied, all previous works considered the cell outage problem in their studies. Conversely, in this thesis, a different network failure is considered. Specifically, the analyzed degradation consists of a coverage deterioration in a cell due to a reduction of its transmission power in the downlink. Such an issue may be caused by wiring problems or a wrong parameter configuration. In this situation, the faulty cell is still carrying traffic although its coverage area is reduced due to the fault. Thus, the faulty cell can be considered for the compensation.

Obj.4 *Development of a simulation tool.* Finally, in order to evaluate the previous algorithms, a dynamic LTE system-level simulator will be implemented as part of this thesis.

1.3 Document structure

This thesis is divided into four main parts. Each part is related to the previous objectives, which will be treated independently. Consequently, each of them constitutes one chapter.

Specifically, this document consists of seven chapters. Chapter 1 corresponds to this introduction where the motivation and research objectives are presented. Chapter 2 provides a brief overview of the technical background related to this thesis. The following chapters cover the objectives of this thesis. Chapter 3 describes the implementation of the dynamic system-level LTE simulator used to validate the methods, together with some calibration results. Chapter 4 describes the COD algorithm proposed in this thesis. Chapter 5 is devoted to the proposed COC methodology, presenting the outage analysis technique and the adaptive COC algorithms. Chapter 6 covers the CDC algorithm. Finally, Chapter 7 summarizes the main conclusions of the work and presents future lines of action.

This report also includes a brief summary of the thesis in Spanish as appendix A.

Chapter 2

Technical background

This chapter introduces the technical aspects required to follow the rest of this thesis. The chapter is divided in two parts. The first part presents a brief description of the fundamentals of LTE including the network architecture and the main functions at physical, link and network level. The second part describes the basic concepts of SON. The different functionalities are presented in detail, paying special attention to Self-Healing systems.

2.1 Overview of the LTE system

LTE is a 3GPP standard, which follows the UMTS system, allowing high data rate, low latency and packet optimized radio access networks. This standard is designed to support all kind of IP data traffic, while voice is supported as Voice over IP (VoIP) for better integration with multimedia services. Both data and voice services are supported over the same packet switched network [47, 48, 2].

2.1.1 LTE architecture

LTE system is also known as Evolved Packet System (EPS). Fig. 2.1 shows the EPS architecture, consisting of two elements: the Evolved Packet Core (EPC) and the air interface named Evolved Universal Terrestrial Radio Access Network (E-UTRAN).

The core network, EPC, is optimized for IP connectivity and it does not involve support for circuit switched domain. The main elements that constitute the EPC are the following [49]:

- Mobility Management Entity (MME), which is the central element in the EPC, providing a logically direct control plane connection with the User Equipment (UE). MME is responsible for:
    - Non-access stratum (NAS) signaling and NAS signaling security

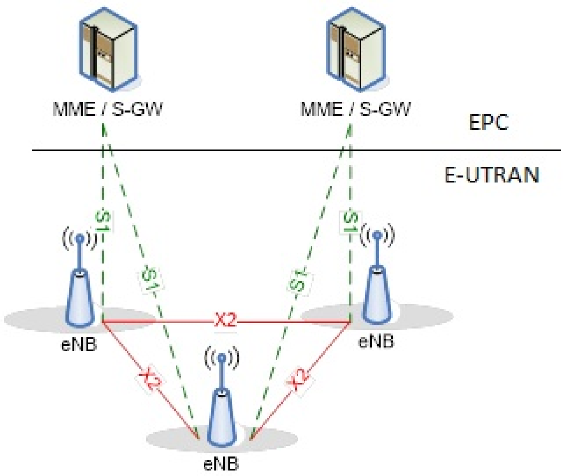

Figure 2.1: LTE overall architecture [2].

- Access stratum (AS) security control
- Idle state mobility handling
- EPS bearer control

- Serving Gateway (S-GW), which is the user plane gateway to the E-UTRAN. The S-GW provides these functions:
  - Mobility anchor point for mobility between LTE cells or cells from other 3GPP technologies
  - Termination of user plane packets for paging reasons
  - Packet forwarding, routing, and buffering of downlink data for UEs that are in LTE-IDLE state
- Packet Data Network Gateway (P-GW), which is the user plane gateway to the packet data network. The P-GW is responsible for policy enforcement, charging support, and user's IP address allocation. It also serves as a global mobility anchor for mobility between 3GPP and non-3GPP access networks. The P-GW is the edge router between EPS and external packet data networks.

The E-UTRAN consists of one node only, the eNB (eNodeB), which is the interface to the UE. eNBs are connected to neighboring eNBs through the X2 interface and with the core network elements through the S1 interface. The eNB hosts these functions:

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

- Scheduling and transmission of paging messages and broadcast information
- Measurement and measurement reporting configuration for mobility and scheduling

Fig. 2.2 summarizes the main functions included in each element of the LTE system. Among these functions, one of the most important function is the RRM. The purpose of RRM is to ensure the efficient use of the available radio resources in order to provide large variety of services to a large number of users, whilst also ensuring Quality of Service (QoS) requirements. Most RRM functions are included in the link and network layer.

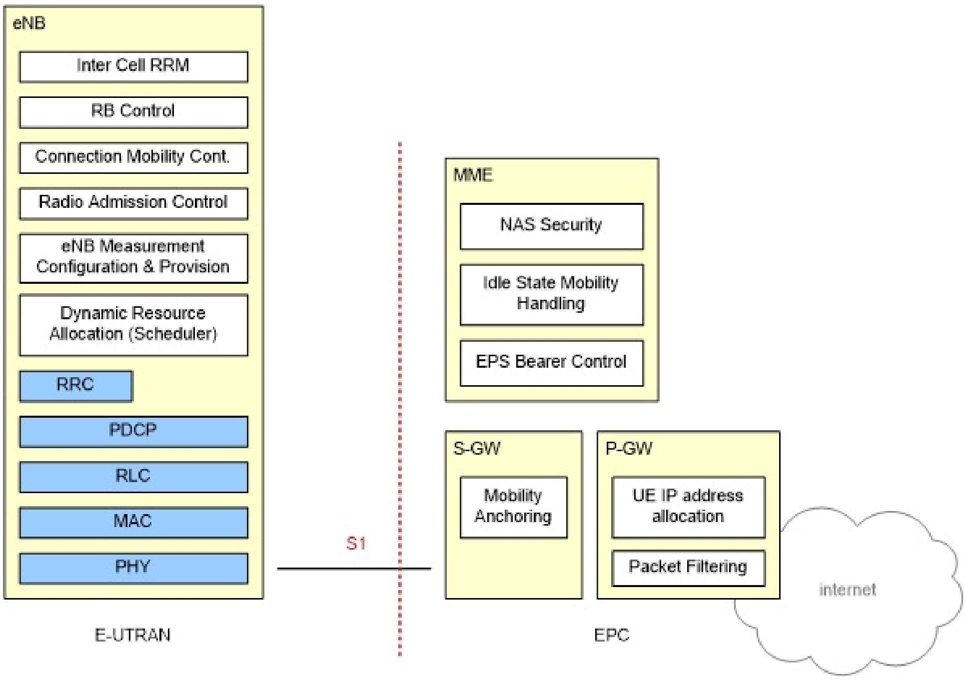

Figure 2.2: Functional Split between E-UTRAN and EPC [2].

2.1.2 Physical layer

Downlink and uplink transmission in LTE are based on the use of multiple access technologies, namely Orthogonal Frequency Division Multiple Access (OFDMA) for the downlink, and Single-Carrier Frequency Division Multiple Access (SC-FDMA) for the uplink.

OFDMA is a variant of Orthogonal Frequency Division Multiplexing (OFDM). OFDM makes use of a large number of closely spaced orthogonal subcarriers that are transmitted in parallel. Each subcarrier is modulated with a conventional modulation scheme (such as QPSK, 16QAM, or 64QAM) at a low symbol rate. The combination of thousands of subcarriers enables data rates similar to conventional single-carrier modulation schemes in the same bandwidth. This technique creates high peak-to-average signals, which is the major drawback in the uplink. Alternatively, SC-FDMA is the transmission scheme chosen for the LTE uplink. This technique combines the low peak-to-average ratio of single-carrier transmission systems, such as GSM and Code-Division Multiple Access (CDMA), with the multi-path protection and flexible frequency allocation of

OFDMA.

In LTE, a Resource Element (RE) is the smallest unit in the physical layer, consisting of one OFDM or SC-FDMA symbol in the time domain and one subcarrier in the frequency domain. These REs are grouped in a Physical Resource Block (PRB) that is the smallest unit that can be scheduled for transmission. A PRB physically occupies 0.5 ms (1 slot) in the time domain and 180 kHz in the frequency domain. The number of subcarriers per RB and the number of symbols per RB vary as a function of the cyclic prefix length and subcarrier spacing. In particular, a PRB comprises 12 subcarriers at a 15 kHz spacing. In addition to the user data, reference signals and other control data are included in each PRB.

Another important feature of LTE is the use of multiple antenna techniques, which are used to increase network coverage and capacity. Such a technique is known as Multiple-Input, Multiple-Output (MIMO) technique. MIMO increases spectral capacity by transmitting multiple data streams simultaneously in the same frequency and time, taking full advantage of the different paths in the radio channel.

2.1.3 Link layer

The link layer is divided into three sublayers: Medium Access Control (MAC), Radio Link Control (RLC) and Packet Data Convergence Protocol (PDCP).

The main services and functions of the MAC sublayer include:

- Mapping between logical channels and transport channels
- Multiplexing/demultiplexing of MAC Service Data Units (SDUs) belonging to one or different logical channels into/from Transport Blocks (TBs) delivered to/from the physical layer on transport channels
- Scheduling information reporting
- Error correction through Hybrid Automatic Repeat reQuests (HARQ)
- Priority handling between logical channels of one UE
- Priority handling between UEs by means of dynamic scheduling
- Multimedia Broadcast Multicast Service (MBMS) identification
- Transport format selection
- Padding

The RLC sublayer includes the following functions:

- Transfer of upper layer Packet Data Units (PDUs)
- Error Correction through Automatic Repeat reQuest (ARQ)
- Concatenation, segmentation and reassembly of RLC SDUs

- Re-segmentation of RLC data PDUs
- Reordering of RLC data PDUs
- Duplicate detection
- Protocol error detection
- RLC SDU discard
- RLC re-establishment

Finally, the main services and functions of the PDCP sublayer include:

- Header compression and decompression
- Transfer of user data
- In-sequence delivery of upper layer PDUs at PDCP re-establishment procedure for RLC Acknowledge Mode (AM)
- Duplicate detection of lower layer SDUs at PDCP re-establishment procedure for RLC AM
- Retransmission of PDCP SDUs at handover (HO) for RLC AM
- Ciphering and deciphering
- Timer-based SDU discard in uplink
- Ciphering and Integrity Protection (control plane)
- Transfer of control plane data (control plane)

As for the RRM, the link layer includes three main functions: HARQ, Adaptive Modulation and Coding (AMC) and user scheduling. HARQ is a technique for ensuring that data is sent reliably from one network node to another, identifying when transmission errors occur and facilitating retransmission from the source. AMC is the mechanism used for link adaptation to improve data throughput in a fading channel. This technique changes the downlink Modulation and Coding Scheme (MCS) based on the channel conditions of each user. When the link quality is good, the system can use a higher order modulation scheme (more bits per symbol) or less channel coding, which results in higher data rates. When link conditions are poor because of problems such as signal fading or interference, the system can use a lower modulation depth or stronger channel coding to maintain acceptable margin in the radio link budget. The scheduler is part of the MAC layer and controls the assignment of uplink and downlink resources. Uplink and downlink scheduling are separated in LTE and uplink and downlink scheduling decisions can be taken independently of each other. The basic principle for the downlink scheduler is to dynamically determine, in each 1 ms interval, which terminal transmits or receives data and on which resources.

2.1.4 Network layer

The main services and functions of the Radio Resource Control (RRC) sublayer include:

- Broadcast of System Information related to the AS and the NAS
- Paging
- Establishment, maintenance and release of an RRC connection between the UE and E-UTRAN
- Security functions including key management
- Establishment, configuration, maintenance and release of point to point radio bearers
- Mobility functions: cell selection and reselection, HO
- Establishment, configuration, maintenance and release of radio bearers for MBMS services
- QoS management functions
- UE measurement reporting and control of the reporting
- NAS direct message transfer to/from NAS from/to UE

The RRC layer includes most of the main functions for the radio resource management. The most significant are the following:

- Radio Bearer Control (RBC). This function is in charge of the establishment, maintenance and release of radio bearers. When setting up a radio bearer for a service, RBC takes into account 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 or other reasons. RBC is involved in the release of radio resources associated with radio bearers at session termination, HO or at other occasions.
- Radio Admission Control (RAC). The task of RAC is to admit or reject the establishment requests for new radio bearers. For this purpose, RAC takes into account 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 as long as radio resources available) while ensuring proper QoS for in-progress sessions (by rejecting radio bearer requests when they cannot be accommodated).
- Connection Mobility Control (CMC). CMC is concerned with the management of radio resources in connection with idle or connected mode mobility. In idle mode, the cell reselection algorithms are controlled by setting parameters (thresholds and hysteresis values) that define the best cell and/or determine when the UE should select a new cell. Likewise, E-UTRAN broadcasts the values of parameters configuring UE measurement and reporting procedures. In connected mode, the mobility of radio connections has to be supported. HO

decisions may be based on UE and eNB measurements. In addition, HO decisions may take other inputs into account, such as neighboring cell load, traffic distribution, transport and hardware resources and operator defined policies. In particular, the physical layer measurements considered in the mobility decisions are:

- Reference Signal Receive Power (RSRP). This measurement is the most basic of the UE physical layer measurements, consisting of the linear average (in watts) of the downlink Reference Signals (RS) across the channel bandwidth. Since the RS exist only for one symbol at a time, the RSRP measurement is made only on those REs that contain cell-specific RS.

- Reference Signal Receive Quality (RSRQ). This measurement provides an indication of signal quality and is defined as the ratio of RSRP to the E-UTRA carrier Received Signal Strength Indicator (RSSI). RSSI represents the entire received power, including the desired power from the serving cell as well as cochannel interference and other sources of noise. Measuring RSRQ becomes particularly important near cell edge when an HO is performed to the next cell.

2.2 Self-Organizing Networks

Mobile communication networks are increasing in size and complexity significantly. Thus, the automation of network management tasks has become a key element in the definition of new generation mobile networks. The addition of automation features is carried out by implementing SON functions. The main objective of SON is to reduce OPEX and CAPEX, while providing services with a certain quality requirements. The main benefits of introducing SON functions in cellular networks are [50]:

- To reduce installation time and costs
- To reduce OPEX by reducing manual efforts when monitoring, optimizing, diagnosing, and healing the network
- To reduce CAPEX due to better use of network infrastructure and spectrum resources
- To improved network performance
- To improved user experience

SON functions can be implemented in different network elements. Depending on the selected network elements, there are three main alternatives: centralized, distributed and hybrid [51]. In a centralized SON architecture, the algorithms are executed at the network management level. The main benefit of this approach is that the SON algorithms can take information from all parts of the network into consideration. In the case of a distributed SON architecture, SON algorithms are implemented in the network nodes. Thus, the computational load of executing algorithms is distributed across network nodes. A major drawback is the fact that the nodes need to exchange information directly with each other. Finally, the hybrid SON alternative implements part of the SON algorithm in the network management system and another part in the network elements.

Most SON functions share an initial phase of collecting network data that are used to make decisions. Network information can be of different types depending on the source [10]:

- Configuration management parameters (CM). This information consists of the current configuration settings of network elements.
- Performance management parameters (PM). This information consists of counters reflecting the performance of network elements, which are reported periodically and aggregated at different levels. They can be related to traffic load, resource availability, etc.
- Alarms. These are messages generated by the network elements when a failure occurs.
- Mobile connection traces. This data consists of very detailed information of events generated by specific UEs, which can be collected from most network elements.
- Real time monitoring. Some network elements provide online measurements, such as traffic load or HOs.
- Drive tests. Field measurements performed in a specific area with specialized equipment.
- KPIs. These indicators are calculated by combining other counters or measurements to provide a meaningful performance measure. They are the measurements more frequently used as input of SON functions.
- Context information. This is information related to the environment, such as type of area (e.g., urban area) or typical weather in the cell (e.g., rainy).

According to the 3GPP definitions [8, 9], the SON functions can be grouped into three categories, shown in Fig. 2.3:

- Self-Configuration. The objective of this functionality is to reduce the amount of human intervention in the overall installation process by providing "plug and play" functionality in network elements, such as the eNBs. Some tasks of Self-Configuration systems are: the detection of the transport link and establishment of a connection with the core network elements, to download and upgrade to the latest software version, to set up the initial configuration parameters including neighbor relations, to perform a self-test and to set the node to operational mode. The main use cases defined in Self-Configuration are:
  - Automated configuration of physical cell identity. This SON use case provides an automated configuration of a newly introduced cell physical identity. When a new eNB is brought into the field, a physical cell identity needs to be selected for each of its supported cells, avoiding collision with respective neighboring cells.
  - Automatic Neighbor Relation function. This use case allows an eNB to build and maintain neighbor relationships. This function is also important when the network is expanding and even in mature networks.
- Self-Optimization. Self-Optimization functions aim at maintaining adequate service quality and network performance after changes in network operating conditions with a minimum of manual intervention from the operator. These functions monitor and analyze performance

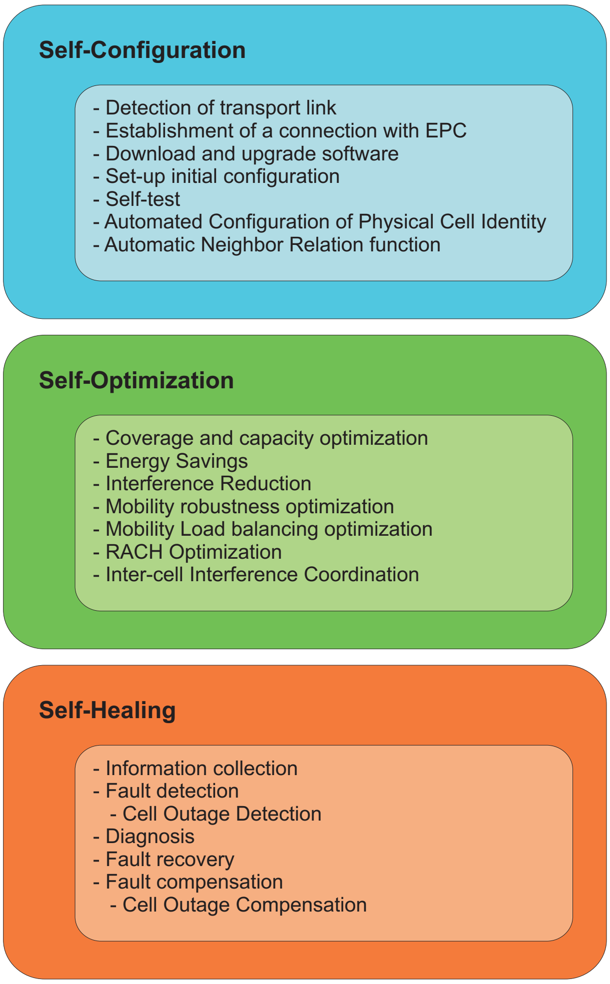

Figure 2.3: SON functions and use cases.

data and automatically trigger optimization actions when necessary. The main use cases in Self-Optimization are:

– Coverage and capacity optimization. A typical operational task is to optimize the network based on coverage and capacity criteria. Coverage optimization has usually a higher priority than capacity optimization. To provide an optimal coverage, users should establish and maintain connections with acceptable or default service quality, according to operator's requirements. It implies that coverage is continuous and users are unaware of cell borders. The coverage must therefore be provided in both, idle and active mode for both, uplink and downlink. Coverage optimization algorithms must take the impact on capacity into account. Since coverage and capacity are linked, a trade-off between the two goals may also be a subject of optimization.

– Energy savings. This use case is based on switching off a cell when its capacity is no longer needed and re-activate it on a need basis in order to reduce operational expenses.

– Interference reduction. The objective of this use case is to improve the capacity through interference reduction by switching off those cells that are not needed at some point of time (e.g., home eNBs when the user is not at home).

  - Mobility robustness optimization. The objective of this use case is to automatically modify the HO configuration parameters in order to reduce the degradation of the service performance caused by a non-optimal configuration of HO parameters.
  - Mobility load balancing optimization. This use case is based on the optimization of cell reselection and/or HO parameters to cope with the unequal traffic load distribution and to minimize the number of HOs and redirections needed to achieve the load balancing.
  - Random Access Channel (RACH) optimization. The objective of this use case is to optimize the RACH configuration, which has a significant impact on the system performance, such as call setup delays, call setup rate, HO success rate, HO delays, etc.
  - Inter-cell interference coordination. The objective of this use case is to reduce or avoid the interference between PRBs in uplink and downlink by a coordinated usage of available radio resources in adjacent cells. This coordination is carried out by prioritizing users in the different cells. The main benefit is an improved signal quality and higher user data throughput.

- Self-Healing. Self-Healing functions aim to mitigate as far as possible the performance degradation caused by a problem in a network. Firstly, performance failures that can affect the network should be detected and diagnosed without human intervention. Then, the failure should be recovered or compensated. According to [10], the main functions in Self-Healing are the following:
  - Information collection. As described before, the first phase of a SON algorithm should be to collect information from the network in order to analyze the current status. The more complete the information is, the faster the failures are identified and solved.
  - Fault detection. The objective of this function is to identify cells with problems. Detection includes identifying cells with service outage (COD) and also cells with service degradation (Cell Degradation Detection, CDD).
  - Diagnosis. This function consists of identifying the fault cause of the problem and then determining the repair actions to eliminate that cause.
  - Fault recovery. This function carries out the execution of the identified repair actions to solve the detected failure.
  - Fault compensation. This function tries to minimize the degradation caused by the fault until it is definitely solved. The compensation can be applied when the fault is an outage (COC) or when a cell is degraded (CDC). This function acts in parallel with the diagnosis function.

COD and COC are two of the main use cases in Self-Healing defined by the 3GPP. These two use cases are addressed in this thesis. In a global context where different failures may occur in a network, the detection function may be one of the easiest function in Self-Healing. In many cases, the problematic cell can easily be identified by some specific alarms and KPIs. However, there are certain faulty situations (e.g., cell outages) that may be harder to detect, as they do not generate any alarms [10]. This thesis deals with the latter case, proposing a new COD algorithm. Likewise, a novel COC methodology and a novel CDC algorithm are proposed.

Chapter 3

Simulation tool

In this chapter, a computationally-efficient tool for dynamic system-level LTE simulations is proposed. A physical layer abstraction is performed to predict link-layer performance with a low computational cost. At link layer, there are two important functions designed to increase the network capacity: link adaptation and dynamic scheduling. Other RRM functionalities, such as admission control and mobility management, are performed at network layer.

This chapter is organized as follows. First, Section 3.1 presents the related work. Section 3.2 presents the general simulator structure. Section 3.3 describes the physical layer, focusing on the calculation of the OFDM channel realizations needed for resource planning. Section 3.4 is devoted to the link layer, where link adaptation and resource planning are performed. Section 3.5 outlines the network layer, including admission control, congestion control and mobility management. In Section 3.6, simulation results are presented. Finally, in Section 3.7, the main conclusions are highlighted.

3.1 Related work

The design of efficient simulation tools for LTE networks has been addressed in the literature. Due to the complexity of LTE systems, simulators are usually focused on a specific part of the global network. Thus, simulators focused on the physical layer can be found, as well as others that implement link-level functions and system-level simulators. On the one hand, simulators that implement physical layer and link-level functions usually present very simple scenarios where a few users are considered. For these users, all the functions related to the transmission and reception of information between the user and the base station are analyzed. Some of these functions are modulation and coding, MIMO techniques, retransmission mechanisms, etc. The simulators described in [52, 53, 54] present these characteristics. In [55], a simple physical layer model is proposed for LTE to reduce the complexity of system level analysis. In [56], a link-level simulator for LTE downlink is presented as an appropriate interface to a system level simulator.

On the other hand, system-level simulators are usually focused on radio resource management functions, such as user scheduling, HO or admission control. In this case, more complex scenarios that include several cells are needed, since the analyzed functions have an impact of more than one cell. When the number of considered cells is higher, the number of simulated users increases too. In these simulators, the computational cost of simulating the physical layer is too high. For this reason, this type of simulator usually includes an abstraction of the physical layer. Different system-level simulators are proposed in the literature [57, 58, 59, 60, 61]. Specifically, the authors of [59] propose a simulator that includes the main RRM functions of the link and network layer. In addition, this simulator includes a part of the core network. Alternatively, the simulators presented in [57] and [58] are focused on link level functions, such as link adaptation and user scheduling. In [57], an LTE downlink system-level simulator is proposed under an academic, non-commercial use license. Simulators proposed in [60] and [61] include realistic outdoor and indoor scenarios. For these system-level simulators, it is possible to model the physical layer based on the results obtained by using a link-level simulator. For instance, the physical layer model described in [53] is used in [57].

Many of these simulators are implemented in MATLAB [57, 58], although some of them are implemented in other languages, such as C++, for computational efficiency [59, 52].

3.2 Simulator general structure

The simulator developed in this thesis is conceived for simulating large network time periods to allow evaluation of SON algorithms for the main network-level functionalities. For computational efficiency, the tool is focused on the downlink of E-UTRAN, although it also includes an estimation of uplink performance. The development of the simulator has its origins in an MSc Thesis [62], whose aim was to simulate a GSM network at system level. Since then, several updates have been made to include UMTS [63] and joint RRM for GSM and UMTS [64, 65]. Many people of the Mobile Network Optimization team have been involved in the definition of an LTE module, in particular, in the design of the physical layer and the RRM functions. In the context of this thesis, part of the design process and the development of the LTE module have been carried out.

This section presents the general structure of the LTE simulator developed in MATLAB. Fig. 3.1 shows the main functional blocks of the simulator. The first stage of a simulation is the configuration and initialization of the main simulation parameters, defining the behavior of the main functions in the simulator. The scenario to be simulated is generated here. A warm-up distribution of users is also created by this function, which allows to obtain meaningful network statistics from the first iterations of the simulation. The next function calculates the propagation losses. This function calculates the power received by each user from the base stations of the scenario. The simulator includes a pathloss model, a slow fading model and a fast fading model. During this phase, the interference suffered by each user is also calculated. From this information, the value of the Signal to Interference plus Noise Ratio (SINR) experienced by each user for different frequency subbands is obtained. Once the main parameters of interest have been obtained, the functions of RRM are executed. At link level, the simulator includes link adaptation and resource scheduling functions. The link adaptation function selects the most appropriate MCS for each user to transmit the information, maximizing spectral efficiency. This decision is based on the propagation conditions experienced by the user. The Channel Quality Indicator (CQI) is used to reflect the link conditions. The radio resource scheduling function assigns available radio resources to users based on channel conditions experienced by each user for different frequency subbands. This function is also based on the CQI indicator. At network level, the simulator includes several functions. The main ones are HO and admission control. Lastly, the main results and statistics are shown.

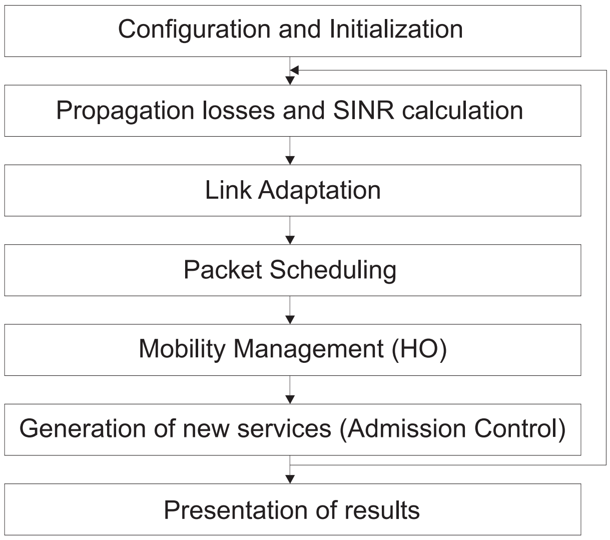

Figure 3.1: Block diagram of the simulator.

3.2.1 Macrocellular scenario

The simulator includes two types of macrocellular scenario: a uniform scenario and a realistic scenario.

Uniform scenario

This scenario models a macrocellular environment, where the number of hexagonal cells is configurable in the simulator. Fig. 3.2 illustrates the layout for a scenario with 19 tri-sectorized sites evenly distributed.

To avoid border effects in the simulation, the simulator incorporates the wrap-around technique described in [66]. Wrap-around consists in creating replicas of the scenario surrounding the original one. Only the original scenario is considered when collecting results and statistics. Fig. 3.3 shows the simulation scenario with the wrap-around technique. Finally, it is necessary to define the set of interfering cells for each cell of the scenario. For each cell, an ordered set of interfering cells are constructed in terms of the power received from each interferer obtained by static system-level simulations.

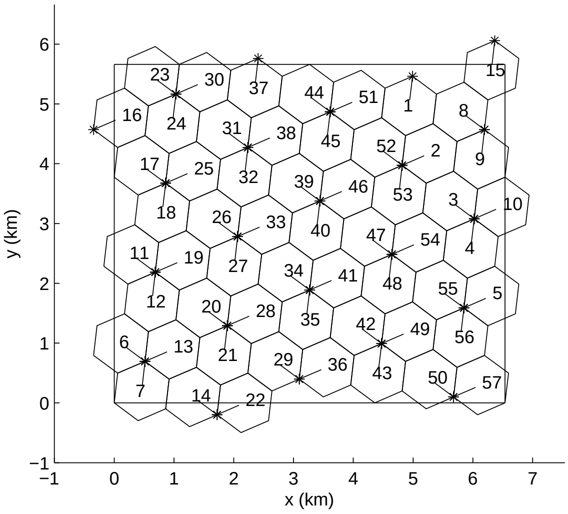

Figure 3.2: Simulation scenario.

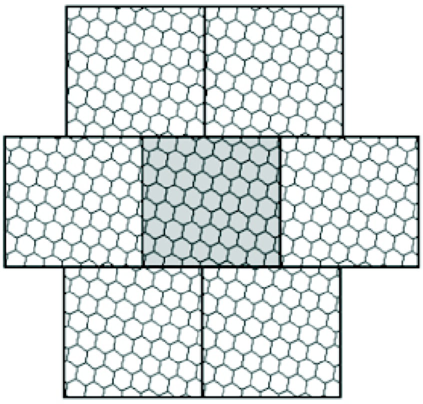

Figure 3.3: Simulation scenario with wrap-around.

Realistic scenario

In addition, the simulator can use a realistic scenario in the simulations. This scenario consists of 75 tri-sectorized cells in a live LTE network. Some configuration parameters (location, antenna azimuth and tilt angles, and HO margin (HOM)) have been obtained from the real network. Fig. 3.4 shows the simulated scenario in a normal situation. The figure shows a coverage map, with the RSRP from the strongest cell in each point of the scenario. In addition, a circle indicates the cells for which statistics are collected. The remaining cells of the scenario are not considered to avoid border effect.

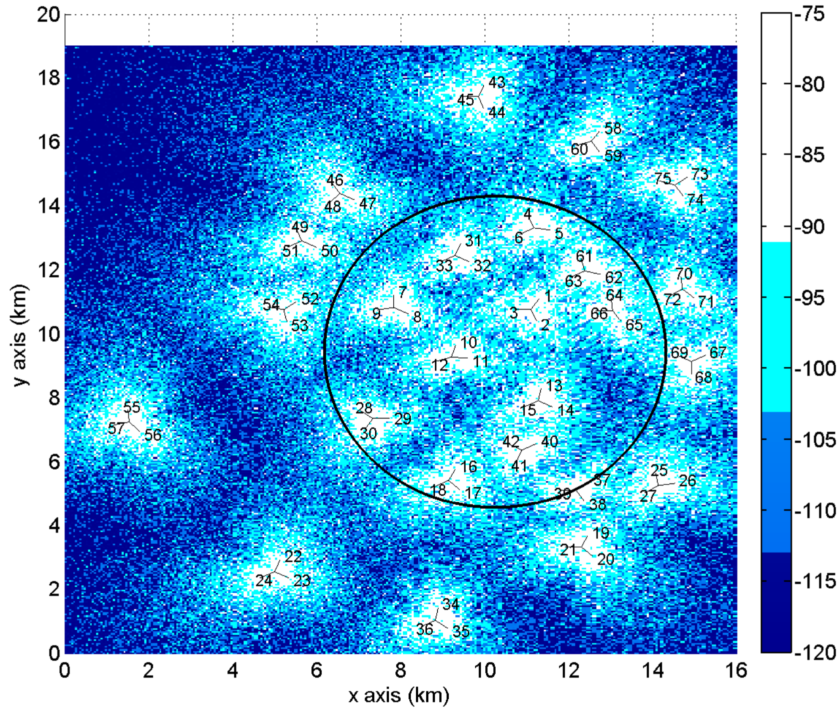

Figure 3.4: RSRP values in the simulation scenario (dBm).

3.2.2 Antenna pattern definition

The simulator includes a 3-D antenna pattern defined as in [67]. The 3-D pattern is approximated by summing up the horizontal and vertical gain patterns in [67]. The horizontal pattern is calculated as follows:

$$A_H(\varphi) = -min[12(\frac{\varphi}{\varphi_{3dB}})^2, A_m] \tag{3.1}$$

where φ is the azimuth angle of the user relative to every base station, φ_{3dB} is the azimuth beam width and A_m is the antenna backward attenuation. The vertical antenna pattern is given by:

$$A_V(\theta) = -min[12(\frac{\theta - \theta_{etilt}}{\theta_{3dB}})^2, SLA_v] \tag{3.2}$$

where θ is the elevation angle of the user, θ_{etilt} is the tilt of the antenna, θ_{3dB} is the elevation beam width and SLA_v is the backward attenuation.

The 3D antenna pattern can be obtained as the sum of the horizontal and vertical pattern as follows:

$$A(\varphi, theta) = -min\left\{-\left[A_H(\varphi) + A_V(theta)\right], A_m\right\} \tag{3.3}$$

Lastly, an antenna gain is also defined. Fig. 3.5 shows the horizontal and vertical pattern calculated as discussed before.

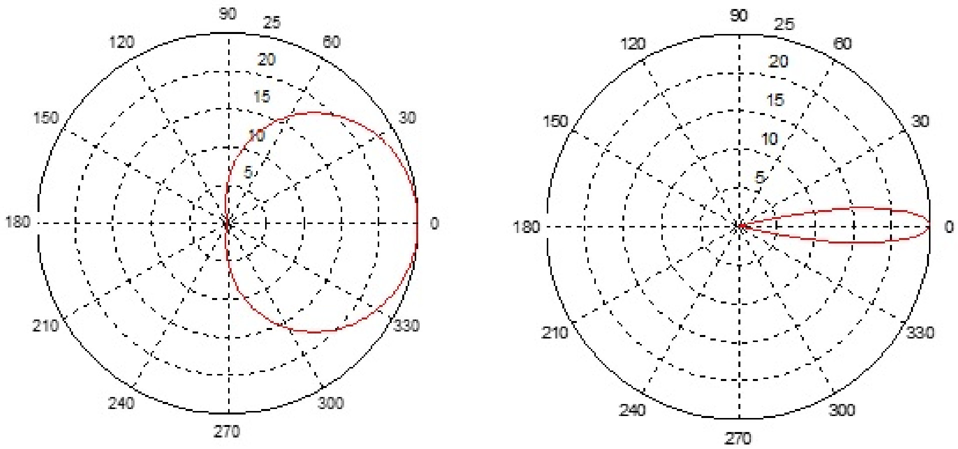

Figure 3.5: Horizontal and vertical antenna pattern.

Alternatively, a real horizontal and vertical antenna pattern can be included in the simulator instead of the aforementioned patterns. Fig. 3.6 shows an example of real antenna pattern.

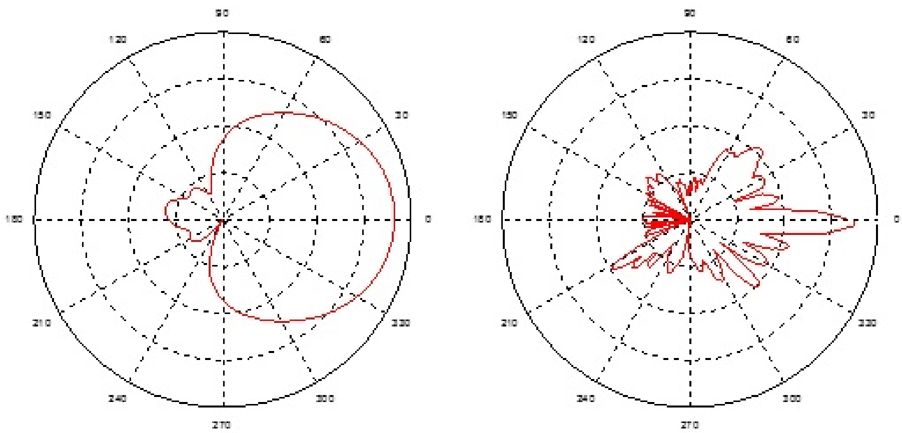

Figure 3.6: Realistic horizontal and vertical antenna pattern.

3.2.3 Spatial traffic distribution

Users can be spatially distributed in a uniform or non-uniform way over the scenario. In the uniform case, users are located in any point of the scenario with the same probability. However, to reproduce a realistic situation, it is recommended to use a non-uniform distribution.

The typical spatial distribution in urban areas can be described by a log-normal distribution at a cell level [68]. In this work, the traffic is created following this distribution with a central hotspot as in [69]. Fig. 3.7 shows the probability of starting a call in any location of the scenario when an uniform scenario is used. It is observed that the spatial traffic distribution has a central peak, creating a congested area with higher traffic density in the center of the scenario. Users can be static or not. In the latter case, spatial traffic distribution is slightly affected by the mobility model, as explained in the next section.

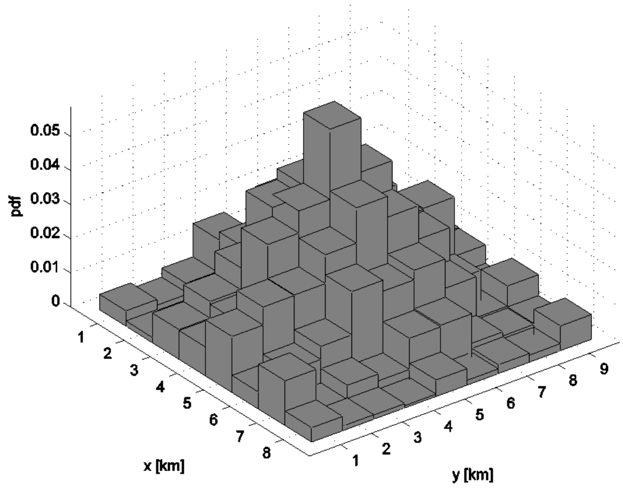

Figure 3.7: Spatial traffic distribution.

3.2.4 Mobility model

The proposed mobility model does not impose any constraint on user direction, as users can freely move over the scenario. More precisely, the mobility model considers random constant paths for users in the simulation scenario. Users move at constant speed, set to 3, 10 or 50 km/h. This model also includes the effect of the wrap-around technique when the uniform scenario is used, which means that when a user reaches the limit of the original scenario, it appears in the correct position of the scenario. In the case that the realistic scenario is used, a random direction is calculated and assigned to each new user. Along the iterations, users move with the assigned direction and the configured speed. The mobility model takes into account scenario boundaries.

3.2.5 Traffic model

The simulator includes two types of service: a voice service and a packet data service. The voice service modeled in the simulator is VoIP. This service is defined as a source generating packets of 40 bytes every 20 ms [70], reaching a bit rate of 16 kbps. As will be described later, the radio resource allocation in the simulator is performed for time intervals of 10 ms. For this reason, the voice service has been implemented as users that transmit packets of 20 bytes every 10 ms.

For data, the service model is similar to the full buffer service. This service is modeled by users with an infinite amount of information to transmit. Thus, a user will transmit with the maximum bit rate if there are available PRBs. This service is mainly conceived for throughput measurements. Service duration is finite (i.e., an random number of seconds).

3.3 Physical layer

3.3.1 Channel model

The mobile radio channel can be described as a time-varying linear filter [71]. Therefore, it can be represented in the time domain by its impulse response, $h(\tau, t)$, where τ stands for delay of each path in h, and the amplitude of each path varies with time t. Also, the channel can be characterized by the time-variant transfer function, $H(f, t)$, which is related with impulse response through the Fourier transform with respect to the delay variable τ.

When the behavior of the channel is randomly time variant, the above-mentioned channel functions become stochastic processes. A realistic approach to the statistical characterization of such a channel may be accomplished in terms of correlation of channel functions since it enables channel output autocorrelation to be determined. Channel autocorrelation functions are related through Fourier transform as well.

For typical physical channels, time fading statistics can be assumed stationary over short periods of time and channel correlation function is invariant under a translation in time t, thus being categorized as wide-sense stationary (WSS). In addition, frequency-selective behavior is stationary in frequency f being the autocorrelation function invariant under frequency translations. This condition is termed uncorrelated scattering (US), and most practical channels satisfy it fairly well.

Autocorrelation functions of wide-sense stationary uncorrelated scattering (WSSUS) channels exhibit the property that the time-variant transfer function autocorrelation is stationary both in time t and frequency f variables, i.e., its value does not depend on the absolute time or frequency considered but only on the time or frequency shift between time or frequency points of observation.

As a consequence, a WSSUS channel can be simulated generating the impulse response, $h(\tau, t)$, with stationary variation in time t for each path and no cross-correlation between different values of delay τ (i.e., generating independent stochastic processes for different paths). Stationarity is achieved by applying Doppler filters to the amplitude time t variation on each path. These filters perform spectrum shaping according to Doppler effect experimented by any radio signal propagating from a transmitter to a moving receiver (or vice versa). Afterwards, the frequency transfer function, $H(f, t)$, can be computed easily by applying the Fourier transform to the impulse response with respect to the delay variable.

To provide the possibility of simulating non-constant speed mobiles, fading realizations cannot be performed over time as an independent variable. Alternatively, space variables have to be used so that channel varies according to the current position of the mobile at each iteration of simulation. Therefore, a fading channel spatial grid has been generated. This grid provides channel responses for every physical position in the simulated scenario, regardless of mobiles speed.

Narrow band fading grid is generated to get a Lord Rayleigh universe [72]. In other words, following Clarke's model [71], a spatial bidimensional complex Gaussian variable is filtered by a bidimensional Doppler filter. The bandwidth of 2-D Doppler filter can be obtained as a function of spatial grid resolution and wavelength size.

Once narrowband channel behavior for each spatial position is obtained, extension to wideband is possible performing the same procedure for every path in power delay profiles described in the specification for Extended Typical Urban (ETU), Extended Pedestrian A (EPA) and Extended Vehicular A (EVA) channels in [73]. Thus, different (uncorrelated) Rayleigh universes are generated for each delay in wideband channel scenario. This results in a distance-variant impulse response $h(\tau, d)$ (autocorrelation) of the channel instead of a time-variant impulse response $h(\tau, t)$ described in [71] as one of the four system functions for complete WSSUS channel characterization. The only difference is the time to distance (t to d) variable change made. A realization of the function is shown in Fig. 3.8.

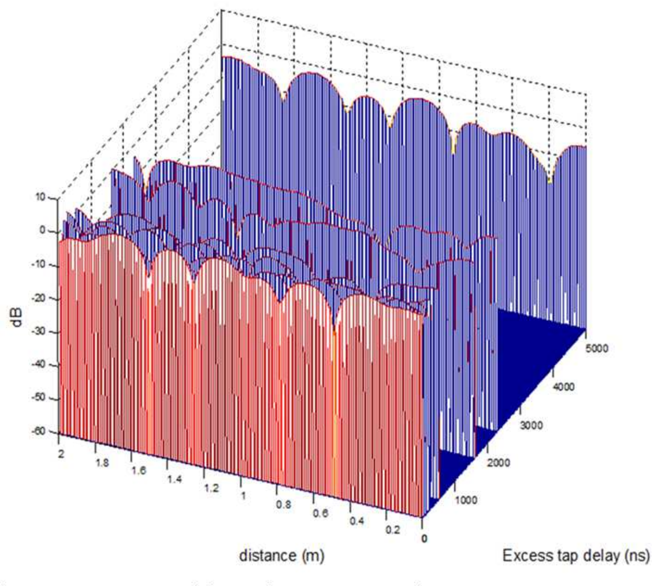

Figure 3.8: Generated bidimensional channel impulse response for ETU channel model in [73].

Since the simulator requires channel realizations for different frequency bands (corresponding to OFDM subcarriers), the distance-variant impulse response has to be transformed into a distance-variant transfer function $H(f, d)$ at each position, by applying Fourier transform with respect to delay variable τ. An example of this function can be seen in Fig. 3.9. The only remaining step is to extend the space variable d of the generated function $H(f, d)$ to a bidimensional (x, y) space variable, obtaining $H(f, x, y)$, a tridimensional function that provides frequency response for each spatial position given by coordinates, x and y.

3.3.2 Radio propagation channel

The radio propagation calculations are made from a set of pre-computed matrices. Thus, it is not necessary to perform the calculations during the simulation. For the definition of the pre-computed propagation matrix, the scenario is divided into a grid, whose resolution is given by

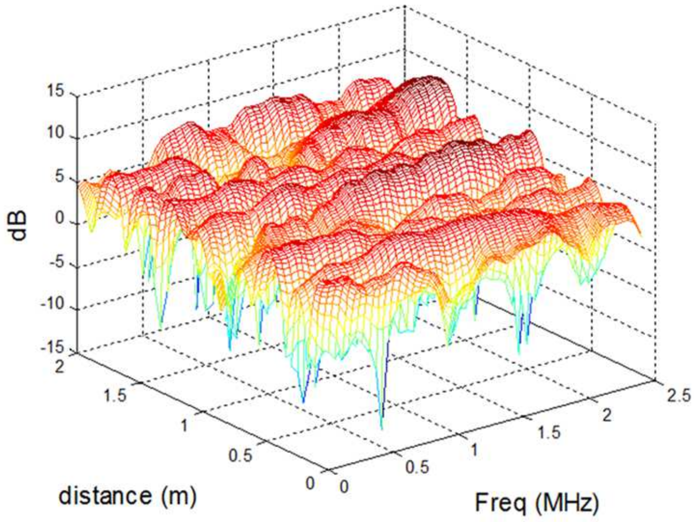

Figure 3.9: Generated distance-variant transfer function for ETU channel model in [73].

the correlation distance of the slow fading (50 m). To compute the propagation loss for a user, it is only necessary to read the index in the matrix corresponding to the position occupied by the user in the scenario relative to every base station and then interpolate it with other values of the matrix depending on the relative position in the grid. The propagation matrices include pathloss and slow fading.

The radio propagation model is the COST 231 extension of Okumura-Hata model [74]. This model is applicable for frequencies in the range from 1500 to 2000 MHz. This model is valid for cell radius between 1 and 20 kilometers, base stations height between 30 and 200 meters and user terminal height between 1 and 10 meters. Equation 3.4 shows the radio propagation model COST 231 - Hata for cities:

$$L = 46.3 + 33.9 \log f_c - 13.82 \log h_b + (44.9 - 6.55 \log h_b) \log r - a(h_m) \,[\text{dB}] \,, \tag{3.4}$$

$$a(h_m) = 3.2(\log(11.75 h_m))^2 - 4.97 \,, \tag{3.5}$$

where f_c is the carrier frequency, h_b is the height of the base station, h_m is the height of the user terminal and r is the distance between the user terminal and the base station. In the developed simulator, the effective height of the base station or eNB antenna has been set to 30 m, while the effective height of the user terminal antenna has been set to 1.5 m. With these assumptions and setting the carrier frequency to 2 GHz, the expression for the pathloss as a function of the distance is given by:

$$L = 137.79 + 35.22 \log r \,[\text{dB}] \,, \tag{3.6}$$

From propagation losses, it is possible to study the link quality experienced by each user in terms of SINR, which is explained in the next section.

3.4 Link layer

3.4.1 SINR calculation

The SINR is a representative measurement of the link quality that the user is experiencing. To calculate the SINR in the simulator, it is first necessary to compute the interference received by each user. It is assumed that intra-cell interference is negligible in LTE, because the scheduler assigns different frequencies and time slots to each user. Thus, only co-channel inter-cell interference due to interfering cells using the same subcarriers is considered. This requires estimating the signal level received from all interfering cells. To calculate the interference from each base station to the terminal, the channel response is not taken into account, but only the pathloss and slow fading.

The SINR calculation for a given subcarrier k, γ_k, is computed using the expression proposed in [75],

$$\gamma_k = P(k) \times \bar{G} \times \left(\frac{N}{N+N_p}\right) \times \frac{R_D}{N_{SD}/N_{ST}}, \tag{3.7}$$

where $P(k)$ represents the frequency-selective fading power profile value for the k^{th} subcarrier, $\bar{G}$ includes the propagation loss, the slow fading, the thermal noise and the experienced interference, N is the Fast Fourier Transform size used in the OFDM signal generation, N_p is the length of the cyclic prefix, R_D indicates the percentage of maximum total available transmission power allocated to the data subcarriers, N_{SD} is the number of data subcarriers per Transmission Time Interval (TTI) and N_{ST} is the number of total useful subcarriers per TTI.

If it is assumed that the multipath fading magnitudes and phases are constant over the observation interval, the frequency selective fading power profile value for the k^{th} subcarrier can be calculated using the expression:

$$P(k) = \left| \sum_{p=1}^{paths} M_p A_p \exp\left(j\left[\theta_p - 2\pi f_k T_p\right]\right) \right|^2, \tag{3.8}$$

where p is the multipath index, M_p and θ_p represent the amplitude and the phase values of the multipath fading respectively, A_p is the amplitude value corresponding to the long-term average power for the p^{th} path, f_k is the relative frequency offset of the k^{th} subcarrier within the spectrum, and T_p is the relative time delay of the p^{th} path. In addition, the fading profile is assumed to be normalized such that $E[P(k)] = 1$.

The value of $\bar{G}$ is calculated from the expression:

$$\bar{G} = \frac{P_{max}\frac{g_n(UE)\times g_{UE}}{PL_{UE,n}\times SH_{UE,n}}}{P_{noise}+\sum_{k=1,k\neq n}^{N} P_{max}\times\frac{g_k(UE)\times g_{UE}}{PL_{UE,k}\times SH_{UE,k}}}, \tag{3.9}$$

where $g_n(UE)$ is the antenna gain of the serving base station in the direction of the user UE, g_{UE} is the antenna gain of the user terminal, P_{noise} is the thermal noise power, $PL_{UE,k}$ is the propagation loss between the user and the eNB k, $SH_{UE,k}$ is the loss due to slow fading between the user and the eNB k and N is the number of interfering eNBs considered.

A PRB is the minimum amount of resources that can be scheduled for transmission in LTE. As a PRB comprises 12 subcarriers, it is necessary to translate those SINR values previously calculated for each subcarrier into a single scalar value. This can be made using the Exponential Effective SIR Mapping, which is based on computing the effective SIR by the equation:

$$SIR_{eff} = -\beta \ln\left(\frac{1}{N_u}\sum_{k=1}^{N_u}\exp\left(-\frac{\gamma_k}{\beta}\right)\right), \tag{3.10}$$

where β is a parameter that depends on the MCS used in the PRB [76] assuming that all subcarriers of the PRB have the same modulation and N_u indicates the number of subcarriers used to evaluate the effective SIR. The values of β have been chosen so that the block error probability for all the subcarriers are similar to those obtained for the effective SIR in an Additive White Gaussian Noise (AWGN) channel [77]. The value of β for a particular MCS is shown in Table 3.1.

Once the SINR has been calculated, the Block Error Rate (BLER) showing the connection quality can be derived. There exist curves that establish the relationship between the values of SINR and BLER defined for an AWGN channel for every modulation and coding rate combination. These curves can also be used to calculate the BLER because inter-cell interference is equivalent to AWGN as the value of β has been selected for this purpose. Then, given the value of BLER and taking into account the MCS used in the transmission, it is possible to calculate the value of throughput, T_i, for each user as follows:

$$T_i = (1 - BLER(SINR_i)) \times \frac{D_i}{TTI}, \tag{3.11}$$

where D_i is the data block payload in bits [78], which depends on the MCS selected for the user in that time interval and $BLER(SINR_i)$ is the value of BLER obtained from the SINR.

3.4.2 Link adaptation

Before explaining the link adaptation function, the 3GPP standardized indicator known as CQI is described. Such an indicator represents the connection quality in a subband of the spectrum. The resolution of the CQI is 4 bits, although a differential CQI value can be transmitted to reduce the CQI signaling overhead. Thus, there is only a subset of possible MCS corresponding to a CQI value [79]. QPSK, 16QAM and 64QAM modulations may be used in the transmission

Table 3.1: Values of β depending on the Modulation and Coding Scheme

Modulation	**Coding**	β **factor**
QPSK	1/3	1.49
QPSK	2/5	1.53
QPSK	1/2	1.57
QPSK	3/5	1.61
QPSK	2/3	1.69
QPSK	3/4	1.69
QPSK	4/5	1.65
16QAM	1/3	3.36
16QAM	1/2	4.56
16QAM	2/3	6.42
16QAM	3/4	7.33
16QAM	4/5	7.68
64QAM	1/3	9.21
64QAM	2/5	10.81
64QAM	1/2	13.76
64QAM	3/5	17.52
64QAM	2/3	20.57
64QAM	17/24	22.75
64QAM	3/4	25.16
64QAM	4/5	28.38

scheme. In the simulator, the CQI is reported by the user to the base station in each iteration (i.e., 100 ms).

Based on CQI values, the link adaptation module selects the most appropriate MCS to transmit the information on the Physical Downlink Shared Channel (PDSCH) depending on the propagation conditions of the environment. To quantify the link quality for each user and subband of the spectrum, the CQI index is used to provide this information. If the experienced BLER value is required to be smaller than a specific value given by the service, it is possible to establish a SINR-to-CQI mapping that allows to select the most appropriate MCS from a given SINR value [53]. The standard 3GPP defines a 5-bit MCS field of the downlink control information to identify a particular MCS. This leads to a greater variety of possible MCSs. For simplicity, the developed LTE simulator includes only the same set of MCS given by the CQI index. From the SINR value, the CQI index is calculated and the MCS can be determined for the next time interval. In the developed simulator, Fig. 3.10 and 3.11 have been used for the SINR-to-CQI mapping.

Once the MCS is selected, the throughput can be estimated based on the efficiency corresponding to each MCS [80].

3.4.3 Resource scheduling

The resource scheduling can be decomposed into a time-domain and frequency-domain scheduling. On the one hand, it is necessary to determine which user transmits at the following time

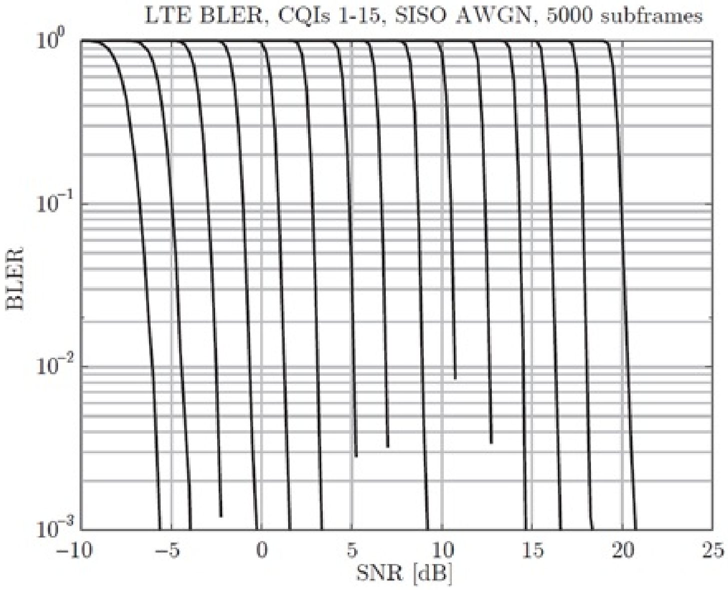

Figure 3.10: SINR-to-BLER mapping, [53].

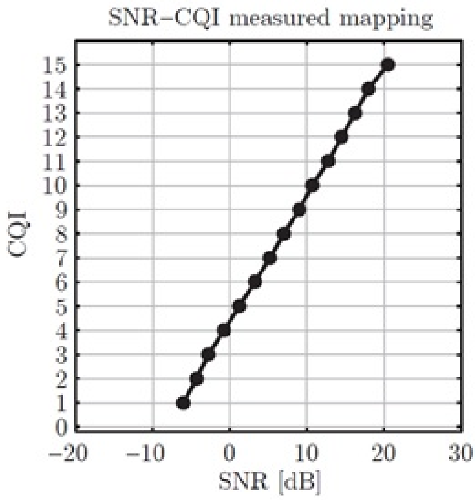

Figure 3.11: SINR-to-CQI mapping for a BLER<10%, [53].

interval. On the other hand, the frequency-domain scheduler selects those subcarriers within the system bandwidth whose channel response is more suitable for user transmission. For this purpose, the channel response for each user and for each subcarrier of the system bandwidth has to be estimated. Such a piece of information is given by the channel realizations generated in the initialization phase of the simulation, assuming a perfect estimation of the channel response. To select the most appropriate frequency subband for the user, the CQI index is used.

The developed simulator includes different strategies for radio resource scheduling. In all of them, the CQI parameter gives the information of the channel quality experienced by each user.

Likewise, scheduling is done for each cell at each iteration following the configured strategy [81]. The scheduling algorithms implemented in the simulator are:

- *Best Channel Scheduler* (BC): in this scheduler, both time-domain and frequency-domain scheduling are done for a more efficient use of resources. At each iteration, all users are sorted based on the quality experienced for each PRB, which is obtained from CQI values. Once users are sorted, allocation procees until there are not available radio resources or no more users to transmit.

  The resource allocation is made by the following expression:

$$\hat{i}[n] = \arg\max_{i}\{r_{ik}[n]\}, \tag{3.12}$$

  where $\hat{i}$ is the selected user i and r_{ik} is the estimated achievable throughput for PRB k and user i obtained from the CQI.

  This scheduling algorithm maximizes the overall system efficiency because the resource allocation is done looking for the combinations PRB-user with better channel conditions. The disadvantage of this algorithm is that harms users with bad channel conditions. Thus, if a user is far from the serving eNB or it is under a deep fading for a large period of time, it cannot be scheduled and it can suffer significant delays.

- *Round Robin to Best Channel Scheduler* (RR-BC): this scheduler uses different strategies for time-domain and frequency-domain scheduling. For time-domain scheduling, the Round Robin method is applied. Thus, users are selected cyclically without taking into account the channel conditions experienced by each of them. Then, each PRB is assigned to the user with a higher potential transmission rate for that PRB. Transmission rate is estimated based on the user's CQI value for each PRB.

  At each iteration, and for each base station, the expressions to be evaluated are:

$$\hat{i}[n+1] = (\hat{i}[n]+1) \mod N_u \tag{3.13}$$

  and

$$\hat{k}[n] = \arg\max_{k}\{r_{ik}[n]\}, \tag{3.14}$$

  where $\hat{i}$ is the selected user, N_u is the number of users and $\hat{k}$ represents the PRB selected. In this case, the goal is to maximize system efficiency, but trying not to harm users with unfavorable channel conditions.

- *Large Delay First to Best Channel Scheduler* (LDF-BC): this scheduler is similar to the previous one only differing in time-domain scheduling. In this case, instead of cyclically selecting the users, they are sorted by the time they have spent without transmitting. Thus, if for some reason, such as a fading prolonged in time, the user has not been allocated in previous iterations, then he will get a higher priority in the current iteration.

  As in the previous case, at each iteration and for each base station, the allocation is carried out based on the following terms:

$$\hat{i}[n] = \arg\max_i \{W_i[n]\}, \tag{3.15}$$

and

$$\hat{k}[n] = \arg\max_k \{r_{ik}[n]\}, \tag{3.16}$$

where $W_i[n]$ is the number of iterations without transmitting for user i. At the end of each iteration, the value of $W_i[n]$ is updated for all users based on whether they have been allocated or not.

- *Proportional Fair* (PF): this scheduler is similar to BC, but it tries not to harm users with worse channel conditions. The objective of PF is to find a balance between getting the maximum possible efficiency of the channel and keeping fairness between users. To this end, scheduling is not only based on the potential transmission rate, but also takes into account the average transmission rate of the user in previous iterations. The algorithm follows the expression:

$$\hat{i}[n] = \arg\max_i \left\{ \frac{r_{ik}[n]}{\bar{r}_i} \right\}, \tag{3.17}$$

where $\bar{r}_i$ is the average transmission rate experienced by user i.

3.5 Network layer

The success of cellular networks is based on the fact that users can obtain global service while moving (coverage, access, etc.). While physical and link levels define transmission characteristics along the UE-eNB link, network level manages all base stations, terminals and their resources as a whole.

The main network level functionalities rely on RRM processes. In live networks, RRM algorithms are vendor dependent. This section describes the admission control, congestion control and HO algorithms implemented in the simulation tool. It should be pointed out that, although scheduling is also usually labeled as an RRM technique, it has already been described in previous sections, since it is located at link level in the simulation tool. Another procedure implemented in the simulator is directed retry, which is triggered when the cell where the UE is camped is in congestion and the UE is assigned to a traffic channel in a cell other than the serving cell.

3.5.1 Admission control

Once a UE decides to start a connection, a first decision is which cell will serve that connection. Such a decision is taken through two main steps:

- *Minimum RSRP*: the UE collects and sends RS received levels from the serving cell and its neighbors to the network. Cells are ranked from higher to lower levels and candidate cells for serving the call are those fulfilling:

$$RSRP(i) \geq MinThresholdLEV(i)\ , \tag{3.18}$$

where $RSRP(i)$ is a wideband measurement reflecting the received level for the RS in cell i and $MinThresholdLEV$ is the minimum required signal level to be accepted, defined on a cell basis. Finally, the best cell i in the list is selected.

- *Enough free resources*: the availability of free PRBs in the best cell is then checked. Note that the mobile network does not know how many PRBs will the user data connection require once it is admitted. Signal level measurements are taken from the RS, but radio channel conditions might be completely different for the finally assigned data radio channel (e.g., fast fading, interference,...). That is the reason why a worst-case criterion has been taken in the simulator to accept UEs. Thus, the UE is finally accepted if:

$$freePRB(i) \geq MaxPRB(serv)\ , \tag{3.19}$$

where $freePRB(i)$ is the number of PRBs available in cell i and $MaxPRB(serv)$ is the worst-case PRB requirement (i.e., the highest number of PRBs needed to maintain a connection) that a specific type of service, $serv$, would demand along the entire connection.

If there are not enough free PRBs, the next candidate cell in the list is checked. A user connection is blocked when no cell fulfills (3.18) and (3.19).

3.5.2 Congestion control

Congestion control avoids congestion situations in the network. As a result of largely uncontrollable factors, such as user mobility, traffic fluctuation or propagation effects, overload situations can occur in a cell, even if admission control is executed to avoid these situations.

This technique is carried out by defining a pool of radio resources that will be assigned differently than by admission control. Operators give priority to ongoing connections over fresh calls [82]. If both fresh and ongoing users are in conflict for the same radio resources (e.g., an HO and a fresh connection occur simultaneously), existing users should be first scheduled. With that aim, fresh users are not accepted in a cell if:

$$LR(i) \geq LR_{threshold}\ , \tag{3.20}$$

where $LR(i)$ is the cell load ratio in cell i (i.e., PRB utilization ratio) and $LR_{threshold}$ is the congestion threshold. There is a trade-off when selecting the $LR_{threshold}$ value. A too low value might cause call dropping due to rejected incoming HOs, but a too high level could lead to unnecessary call blocking while protected resources are idle.

3.5.3 Handover

The HO algorithm is the main functionality to manage connected user mobility. Classical HO algorithms proposed for LTE and implemented in the simulator are the following:

- *Quality HO* (QualHO). A QualHO is triggered when:

$$RSRQ(i) \leq RSRQ_{threshold}(i) \quad \text{for } TTT^{Qual} \text{ s} , \tag{3.21}$$

  and

$$RSRP(j) - RSRP(i) \geq Margin_{Qual}(i, j) , \tag{3.22}$$

  where TTT^{Qual} is the Time-To-Trigger for this type of HO and $Margin_{Qual}$ is the signal level hysteresis between server and adjacent cells (i and j, respectively). This QualHO aims to re-allocate connections which are experiencing a bad quality connection to other cells. $Margin_{Qual}$ is defined on an adjacency basis.

  For monitoring purposes, a QualHO is classified as an *Interference HO* (IntHO) if, in addition to fulfilling (3.21) and (3.22), it is also satisfied that:

$$RSRP(i) \geq RxLEV^{Interf}_{threshold}(i) \quad \text{for } TTT^{Interf} \text{ s} , \tag{3.23}$$

  i.e., the UE has a high signal level but low signal quality.

- *Minimum Level HO* (LevHO). A LevHO is triggered when:

$$RSRP(i) \leq MinRxLEV_{LevHO}(i) , \tag{3.24}$$

  and

$$RSRP(j) - RSRP(i) \geq Margin_{LevHO}(i, j) , \tag{3.25}$$

  where $MinRxLEV_{LevHO}$ is a minimum signal level threshold. LevHO aims to re-allocate connections experiencing a very low signal level (e.g., when the UE is getting out of the coverage area). LevHO is considered an 'urgent' HO and it must be triggered as soon as possible. Thus, no TTT parameter is considered.

- *Power Budget HO* (PBGT_HO). A PBGT_HO is triggered when:

$$RSRP(j) - RSRP(i) \geq Margin_{PBGT}(i, j) , \tag{3.26}$$

  In this case, there is no triggering condition to be fulfilled. Eq. (3.26) is evaluated periodically every N^{PBGT} s, where N^{PBGT} is the length of the time period between evaluations of the condition. PBGT_HO is not considered an urgent HO, but an optimization algorithm. At the end of a PBGT_HO process, the UE should be connected to the best cell in terms of signal level, provided that $Margin_{PBGT}$ is positive.

3.6 Evaluation of system performance

A set of simulations is carried out to evaluate system performance. In particular, HO and congestion control algorithms are analyzed. In addition, a comparison between scheduler strategies is presented.

3.6.1 Key Performance Indicators

The main KPIs used in the simulations are the following:

- *Call Blocking Ratio (CBR)*

  CBR quantifies how efficiently resources are used and can be determined by the following expression:

$$CBR = \frac{N_{blocked}}{N_{offered}} = \frac{N_{blocked}}{N_{blocked} + N_{accepted}}, \tag{3.27}$$

  where $N_{blocked}$ and $N_{accepted}$ are the number of blocked and accepted calls by the Call Admission Control entity respectively, and $N_{offered}$ is the total number of offered calls.

- *Call Dropping Ratio (CDR)*

  This KPI is widely used for voice service and is defined as:

$$CDR = \frac{N_{dropped}}{N_{finished}} = \frac{N_{dropped}}{N_{dropped} + N_{succ}}, \tag{3.28}$$

  where $N_{dropped}$ is the number of dropped calls, N_{succ} is the number of successfully finished calls and $N_{finished}$ is the total number of finished calls. The simulation tool assumes that a call is dropped when a percentage of data packets are dropped during a specific time interval. Packet dropping may occur not only because there is no enough connection quality to be scheduled, but also because there are no available resources to be scheduled.

- *Transmission delays*

  Two different delay KPIs can be defined: delay due to lack of resources and delay due to low signal quality. Both indicators provide information about the number of simulation steps without any transmission. To perform this measurement, it is necessary to maintain a connection active even when the conditions for a dropped call are fulfilled. In the simulations carried out, these KPIs are only considered for data services.

- *Throughput*

  This indicator is a useful measure of spectral efficiency. User throughput can be calculated using the expression 3.11.

3.6.2 Simulation parameters

The simulated scenarios include a macrocellular environment whose layout consists of 19 tri-sectorized sites evenly distributed in the scenario. The main simulation parameters for the simulations are summarized in Table 3.2.

Table 3.2: Simulation parameters

Parameter	Configuration
Cellular layout	Hexagonal grid, 57 cells (3x19 sites), cell radius 0.5 km
Transmission direction	Downlink
Carrier frequency	2.0 GHz
System bandwidth	1.4 MHz (6 PRBs), 5 MHz (25 PRBs)
Frequency reuse	1
Propagation model	Okumura-Hata with wrap-around Log-normal slow fading, σ_{sf}=8 dB and correlation distance=50 m
Channel model	Multipath fading, EPA model
Mobility model	Random direction, constant speed 3 km/h
Service model	VoIP: Constant bit rate, 16 kbps, Poisson distributed Mobile broadband: Full Buffer
Base station model	Tri-sectorized antenna, SISO, $EIRP_{max}$=43 dBm
Scheduler	Best Channel (BC) Round Robin - Best Channel (RR-BC) Large Delay First - Best Channel (LDF-BC) Proportional Fair (PF) Resolution: 1 PRB
Power control	Equal transmit power per PRB
Link Adaptation	Fast, CQI based, perfect estimation
RRM features	HO: QualHO, LevHO, IntHO, PBGT_HO
HO parameter settings	TTT = 100 ms HO margin = 3 dB $RSRQ_{threshold}$ = -5 dB $MinRxLEV_{LevHO}$ = -105 dBm [83]
Time resolution	Iteration time = 100 TTI (100 ms)

3.6.3 Performance results

Analysis of HO process

This section includes a study of the HO process. The considered HO algorithms are QualHO and PBGT_HO. In addition, the HO ping-pong problem is analyzed. The following figures show different user traces that include the time evolution of several indicators.

Fig. 3.12 shows the performance of QualHO. In this case, the HO is executed when the pilot SINR (i.e., the SINR measured in the RS) experienced by the user is lower than a certain threshold (e.g., -5 dB) during a certain time period (e.g., 400 ms). In addition, the signal level difference between serving and neighboring cell must exceed the HO margin (3 dB).

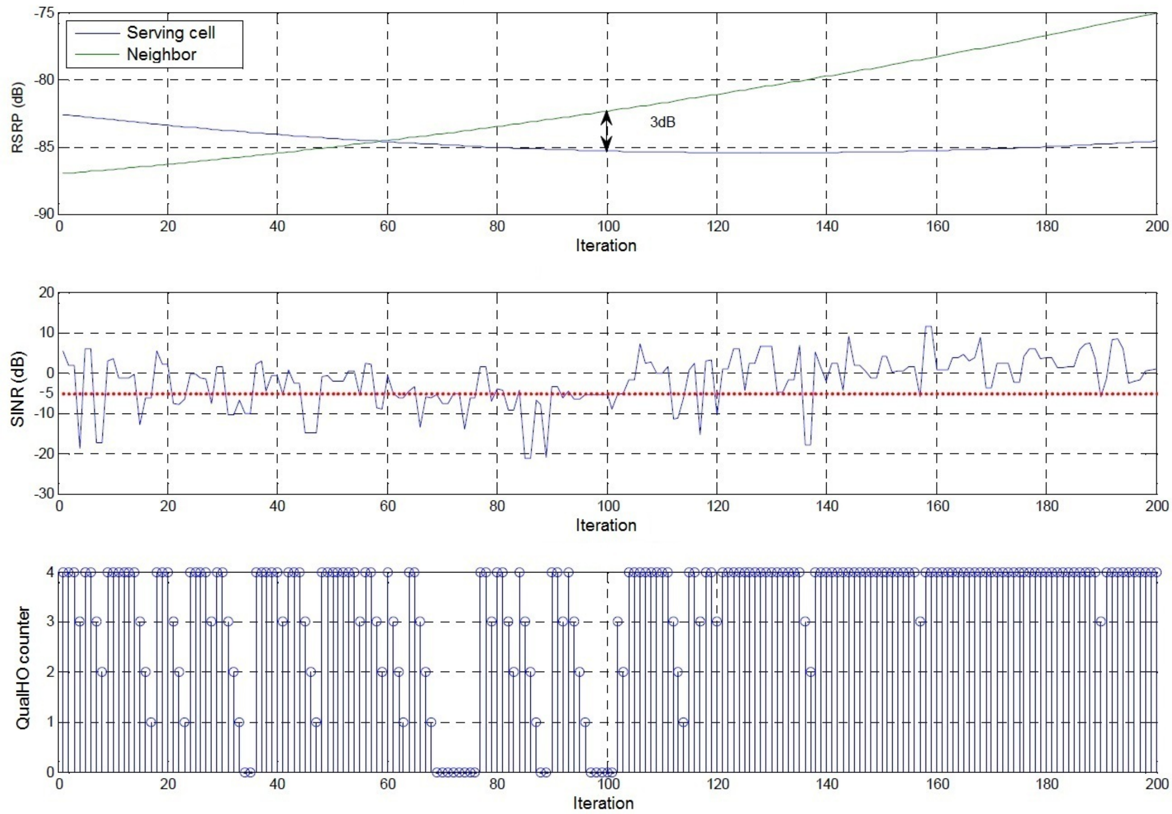

Figure 3.12: User trace for a QualHO execution.

Fig. 3.13 presents the user trace for a PBGT_HO. This algorithm periodically monitors if the HO margin is fulfilled. In this test, the periodicity is configured to 1 s and the HO margin is equal to 3 dB. In the subfigure below, it is observed how the evaluation process is triggered every 10 simulation steps (i.e., 10*100 ms = 1 s).

Finally, Fig. 3.14 present an HO ping-pong event. An HO ping-pong occurs when two (or more) HOs are executed for the same user between the same two cells in a short time period. In this test, this time period is configured to 5 s. In addition, the HO margin has been set to 1 dB

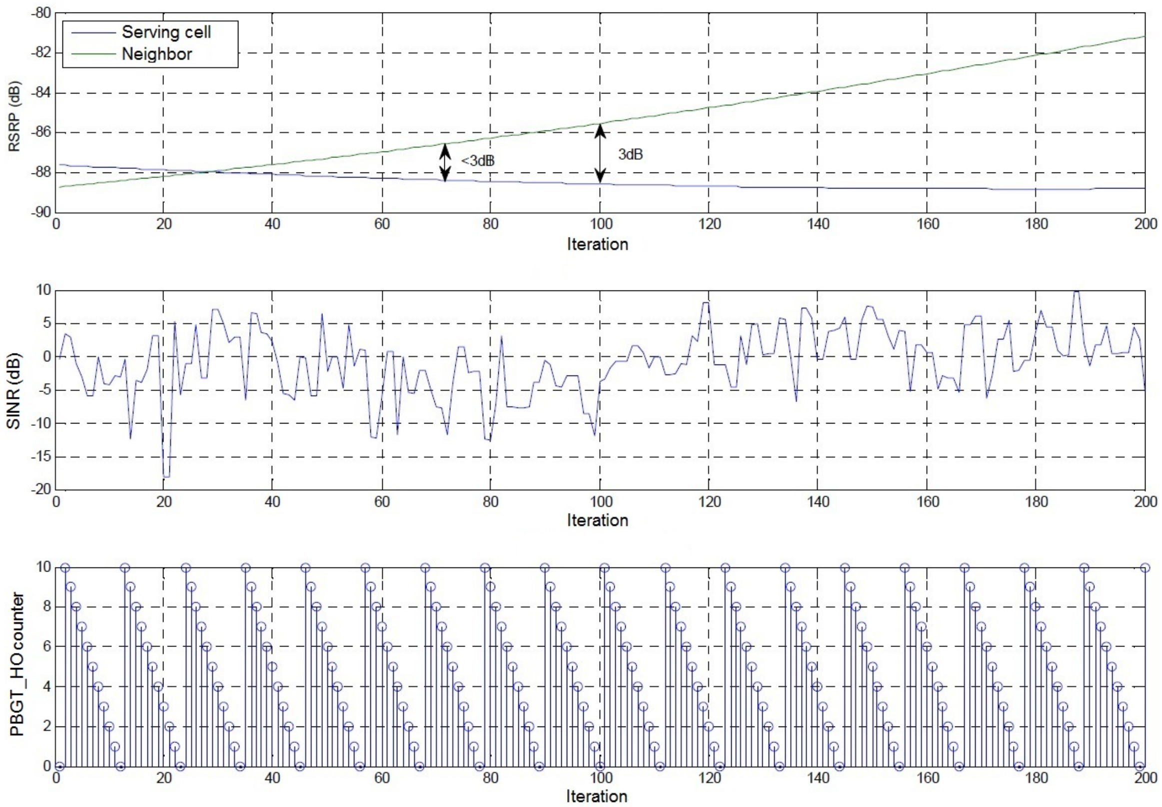

Figure 3.13: User trace for a PBGT_HO execution.

in order to favor the HO ping-pong occurrence.

Congestion control

The aim of the congestion control algorithm is to limit the admission of new connections to ensure the quality of the ongoing connections. In this test, two simulations are carried out. First, a simulation with the congestion control algorithm inactive is executed. The considered service is voice. The selected scheduler is RR-BC because the main requirement of the voice service is a small transmission delay. For convenience, the overall network load is configured to produce a high value of CBR and CDR to ease the analysis of the functionality. The second simulation uses the same configuration but the congestion control is activated and the overall network load is set to 80%. Fig. 3.15 and 3.16 show CBR and CDR results of the 57 cells in the scenario, respectively. In addition, the average values of both indicators is given in Table 3.3. Based on these results, it can be concluded that the congestion control algorithm achieves a significant reduction in the CDR, at the expense of increasing the CBR.

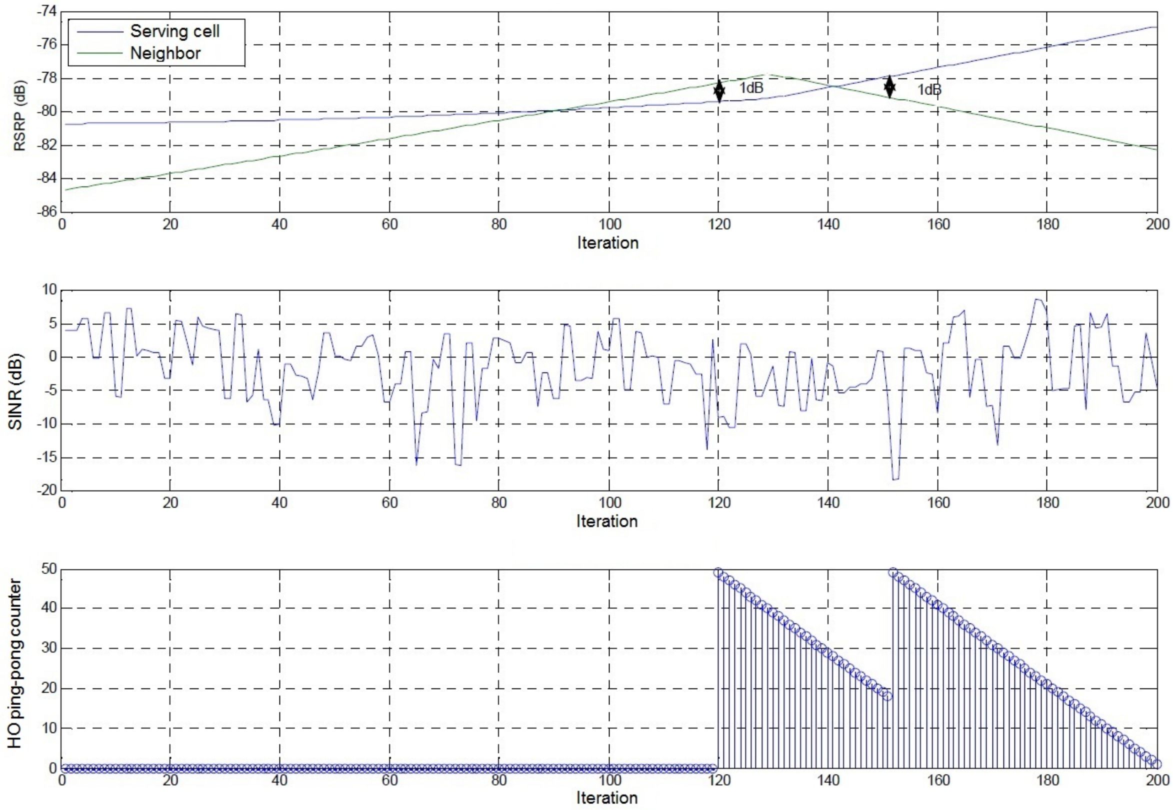

Figure 3.14: User trace for an HO ping-pong event.

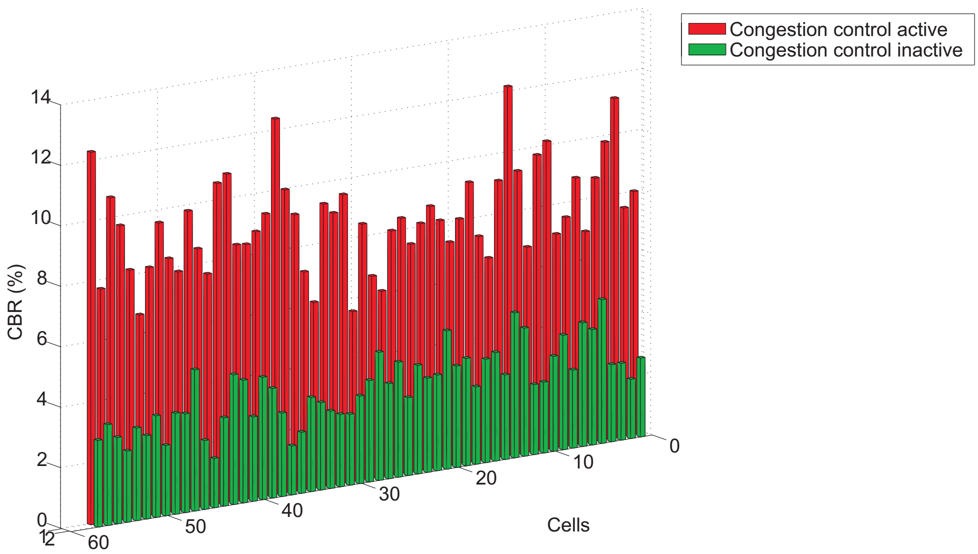

Figure 3.15: CBR.

Analysis of schedulers

In order to study the different scheduler strategies included in the simulator, throughput and delay measurement statistics are analyzed. Fig. 3.17 shows the achieved average user throughput

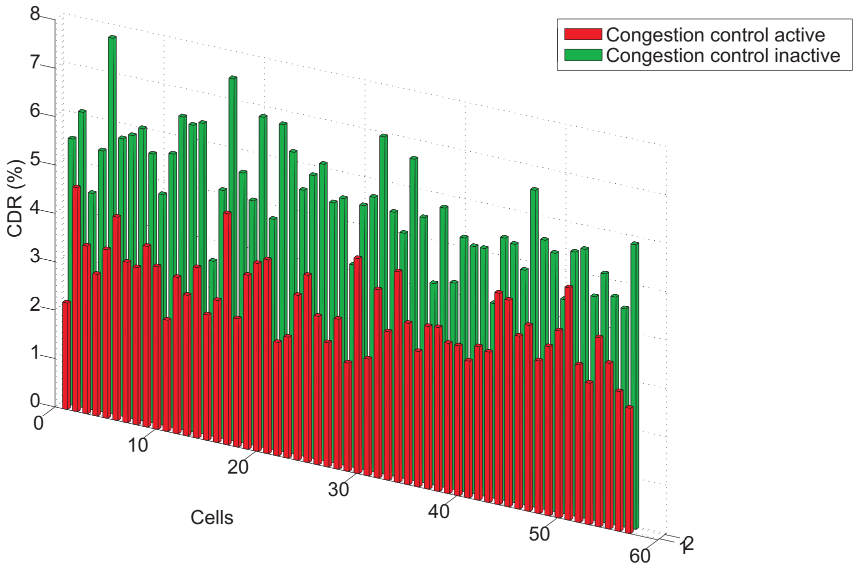

Figure 3.16: CDR.

Table 3.3: Global results of CBR and CDR

	Congestion control inactive	Congestion control active
CBR	3.14%	8.66%
CDR	5.44%	3.31%

per SINR for each scheduler, compared to the upper bound of system capacity obtained with the Shannon formula [53]. It can be seen that the BC and PF strategies achieve higher values of throughput than the RR-BC and LDF-BC. Fig. 3.18 and 3.19 show the cumulative density function (CDF) of transmission delay. From the figure, it is deduced that RR-BC and LDF-BC schedulers obtain the best results. According to these results, it can be concluded that BC achieves the higher throughput values at the expense of penalizing users with the lowest signal quality, which are usually located at the cell edge. RR-BC and LDF-BC aim to avoid large delays for the worst users, resulting in lower average throughput values. PF achieves good throughput values without incrementing the transmission delay of the worst users.

The difference between BC and PF is more noticeable when comparing the average cell throughput, shown in Fig. 3.20. Values obtained for the PF algorithm are lower than that obtained by the BC because, even if throughput per SINR is similar for both schedulers, PF allows bad users to transmit to avoid large delays for these users. Such a different behavior has a large impact on the SINR distribution, shown in Fig. 3.21.

The signal quality experienced by all users (i.e., users that transmit and users that do not transmit) can also be studied by analyzing pilot SINR measurements, as shown in Fig. 3.22. It is observed that the mode (i.e., the most frequent value) is 0 dB. In general, the obtained pilot SINR values are high. The reason is that the simulations have been carried out with a traffic load of 100%. This result is similar for every schedulers.

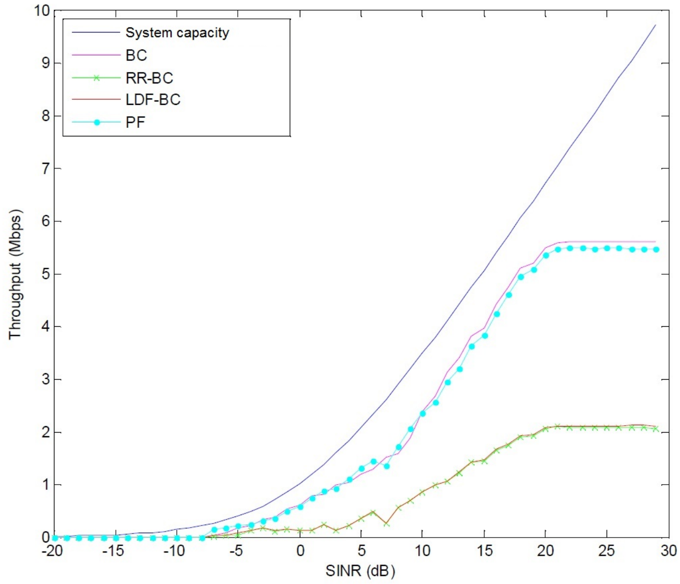

Figure 3.17: Throughput per SINR for different scheduler strategies.

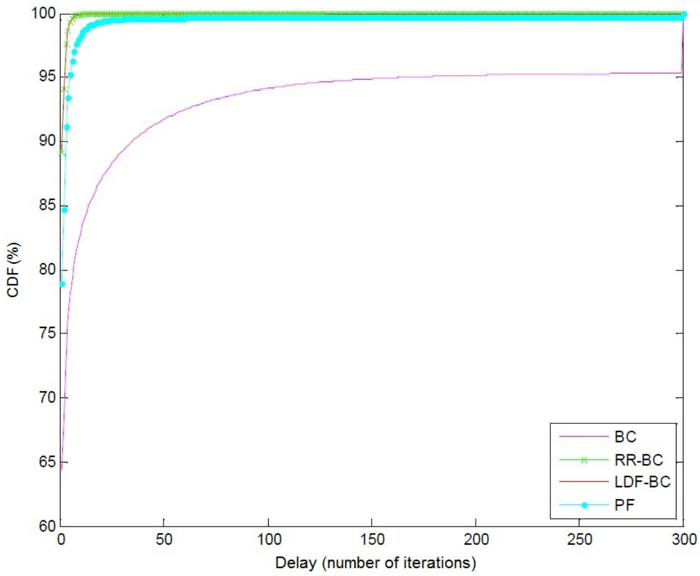

Figure 3.18: Transmission delay distribution due to the lack of resources.

3.7 Conclusions

In this chapter, a computationally-efficient dynamic system-level LTE simulator has been described. This simulator includes the main characteristics of the radio access technology as well as common radio resource management algorithms for improving the spectral efficiency. The simulator is conceived for benchmarking SON algorithms. Thus, the simulator has been implemented to have a low computational cost. A simulation consists of iterations to evaluate the

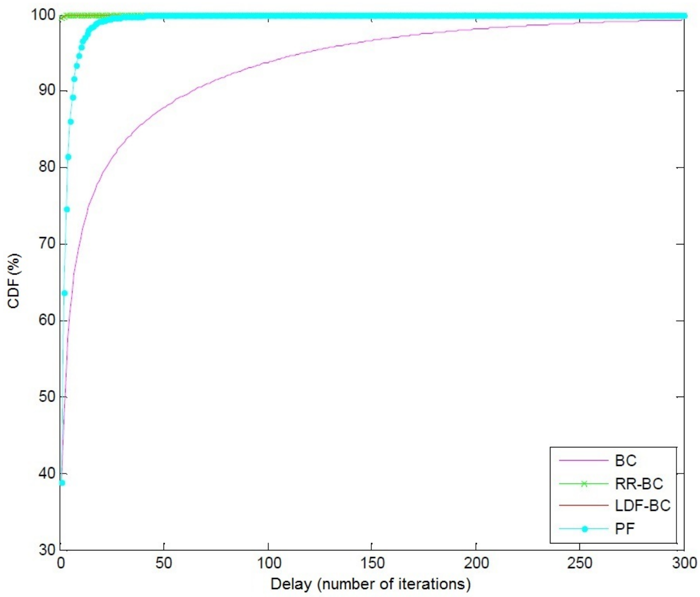

Figure 3.19: Transmission delay distribution due to the lack of quality.

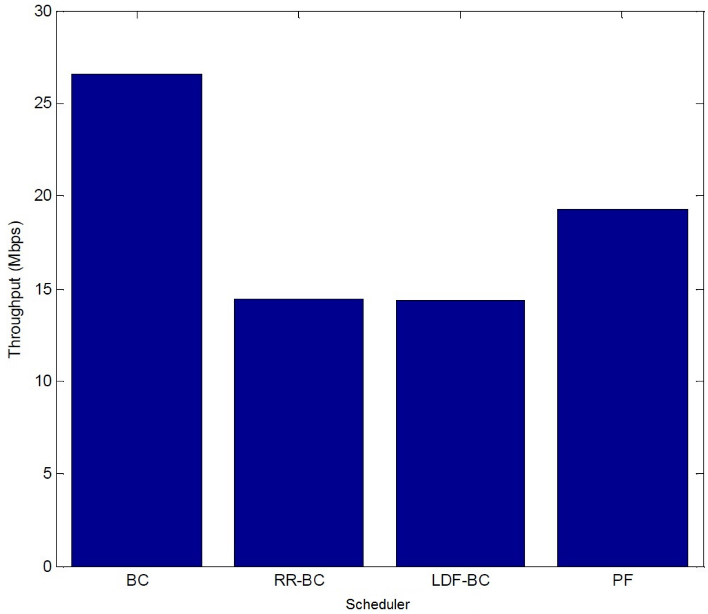

Figure 3.20: Global throughput per cell.

modification of network parameters performed by SON algorithms (e.g., a cell outage compensation algorithm). For a detailed analysis, the simulator provides several indicators at physical and link layers to check the connection quality of mobile users. Such indicators are used as an input to radio resource management functions such as link adaptation and dynamic scheduling. To obtained reliable results, it is essential that these indicators reflect the behavior of the real network accurately. For this purpose, an OFDM channel model has been implemented in the simulator to characterize the time and frequency variation of the radio transmission link for each

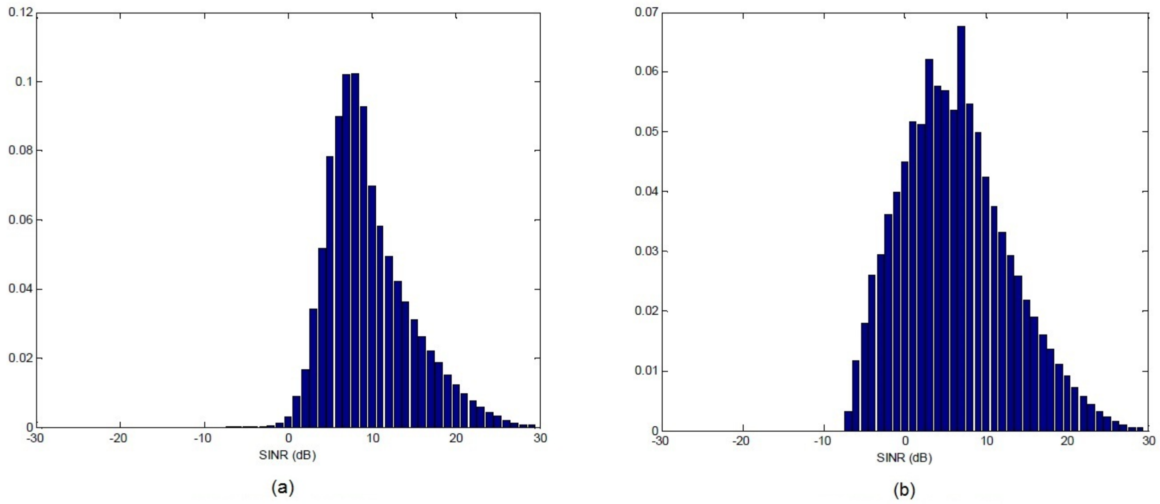

Figure 3.21: Histogram of SINR distribution: (a) BC and (b) PF.

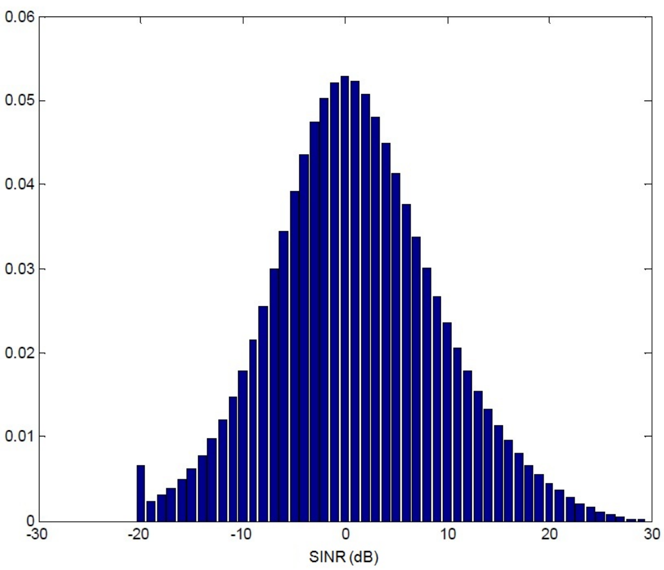

Figure 3.22: Pilot SINR distribution.

user. The main functions of radio resource management have also been described. At network level, the main functions are admission control and mobility management. Finally, several experiments have been carried out with the simulator. Results presented in this chapter include a detailed analysis of classical scheduling, HO and congestion control schemes.

Chapter 4

Cell Outage Detection

This chapter presents a novel cell outage detection algorithm based on incoming HOs statistics. The proposed algorithm is able to detect outages even when the base station is affected, since it is based on measurements collected by neighboring cells. Note that, in this case, no performance indicators from the problematic cell would be available. Section 4.1 introduces the related work found in the literature. The following section, Section 4.2, describes the problem formulation. Sections 4.3 and 4.4 present the proposed algorithm and its evaluation. Finally, Section 4.5 summarizes the conclusions.

4.1 Related work

One of the fundamental use cases in Self-Healing is Cell Outage Management (COM) [84]. COM comprises COD and COC functions. A cell is in outage when it cannot carry traffic due to a failure. In this situation, it is very important to identify the cell in outage as soon as possible to minimize the effects in the network.

There are several methods to implement COD. In most cases [27, 28], the COD algorithm monitors KPIs and alarms reported by cells to determine if they experience problems. Specifically, in [28], the authors propose a method to detect different types of network performance degradation including cells in outage. With this methodology, it is possible to detect outage situations only if the eNB can supply KPIs from the cell in outage to the OSS (Operations Support System). However, if the outage affects the eNB, no KPIs will be available from the cell in outage. When this occurs, the only way to detect an outage in a certain cell is using information provided by its neighboring cells. In this line, in [29] the authors present a COD algorithm to detect outages based on the analysis of the KPIs reported by each cell which allows to determine if any of its neighboring cells is in outage. The effectiveness of this algorithm depends on the severity of problems caused in other cells by the cell outage. This is an important limitation of the algorithm because, in many cases, a cell in outage does not cause a performance degradation in the neighboring cells. The COD algorithm proposed in [30] is based on the neighbor cell list reports. This algorithm can detect cell outages even when the eNB is affected, since the detection is based on user measurements from the neighboring cells. User measurements are also used in [31, 32]. The algorithm presented in [31] is able to detect an outage in a femtocell scenario based on signal level measurements. In [32], the authors propose an algorithm to detect cells in outage based on user measurements combined with location information. However, the use of user measurements is the main drawback of all these approaches because the use of traces limits the bandwidth of the system and operators are unwilling to activate them.

In this chapter, a COD algorithm that overcomes the previous problems is presented.

4.2 Problem formulation

Fig. 4.1 shows different cases of cell outage. In some cases, the fault causing the outage affects only the related cell. In this situation, the related eNB can provide the KPIs from this cell indicating that the cell is not available due to a problem. In other cases, the outage affects the whole eNB. If the latter occurs, there are no KPIs available in the OSS from any cell of the site in outage. Therefore, if the detection algorithm is based on monitoring the value of different KPIs for each cell, this outage situation cannot be detected. Other possible detection algorithms can be based on the lack of KPIs for a certain cell. However, such a lack of KPIs does not always indicate an outage problem. For instance, an eNB-OSS connection failure may cause a lack of KPIs although the related cell is still active.

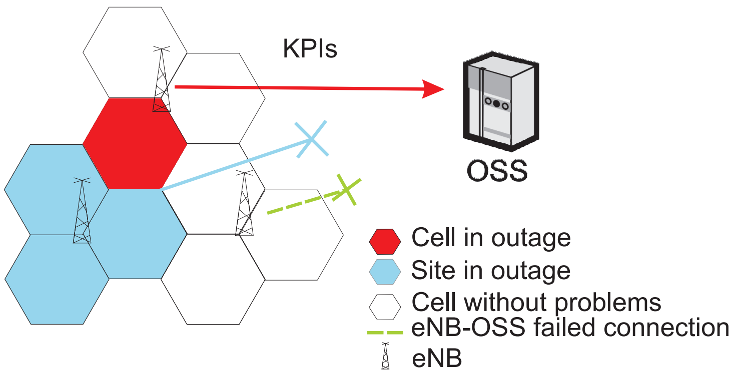

Figure 4.1: Cases of cell outage

To assess different COD algorithms, an LTE system model is proposed here. The considered system model (Cell Outage Model) allows to simulate diverse outage situations so that different detection algorithms can be tested. Moreover, the proposed system model also includes situations that can be detected as outage problems even when the cell operates properly to show the limitations of the algorithms.

The proposed Cell Outage Model includes different cases of cell outage, Fig. 4.1:

- *Cell outage that does not affect the eNB*. In this case there are KPIs available from the cell in outage, although most KPIs are likely to be zero. The eNB indicates that the cell is not active using KPIs related to availability (availability KPIs). In some cases, the cell is automatically locked due to a problem. However, there are also other situations in which the cell is switched off by the operator for maintenance tasks or due to energy saving reasons. In this latter case, switched off cells should not be considered as cells in outage.

- *Site outage*. In this situation the eNB is affected by the fault so that all cells covered by this eNB are impacted. As a consequence, no KPIs can be collected from the OSS.

- *Cell is not in outage, but there is a failure in eNB-OSS connection*. The Cell Outage Model implemented here includes this fault because this situation can be erroneously detected as an outage problem by some detection methods. When an eNB loses the connection with the OSS the KPIs cannot be collected, however, the site is serving traffic.

The Cell Outage Model can be applied to any type of LTE RAN simulator to evaluate different COD algorithms.

4.3 Cell Outage Detection based on incoming handover statistics

The proposed COD algorithm allows to detect a cell in outage even when the eNB is affected and KPIs from that cell are not available. For this purpose, the algorithm is based on neighbor measurements. Specifically, the proposed algorithm monitors the number of incoming HOs (inHO) on a per-cell basis. If this number becomes zero for a certain cell, the algorithm selects the cell as a candidate cell in outage.

The algorithm includes a configurable parameter, called *measurement period*, which determines the time period between two executions of the algorithm. When configuring this parameter, a tradeoff exists between detection delay and statistical significance. The lower the measurement period is, the faster the detection is. However, this parameter has to be high enough to ensure that the collected KPIs are statistically significant and depends on the periodicity of updating KPIs in the OSS.

Fig. 4.2 shows a flow diagram of the proposed COD algorithm. In the first stage, the number of inHO on a per-cell basis is calculated based on HO statistics collected on per-adjacency basis. If it is the first *measurement period* in which the algorithm is activated, the next step is to wait for the next *measurement period* to draw conclusions from the comparison of consecutive periods. Otherwise, the second stage is executed for each cell of the network. Finally, in the third stage, the detected cell outages list is obtained and the algorithm is stopped until the next *measurement period*.

The decision to determine if a cell is in outage is made in the second stage of the algorithm.

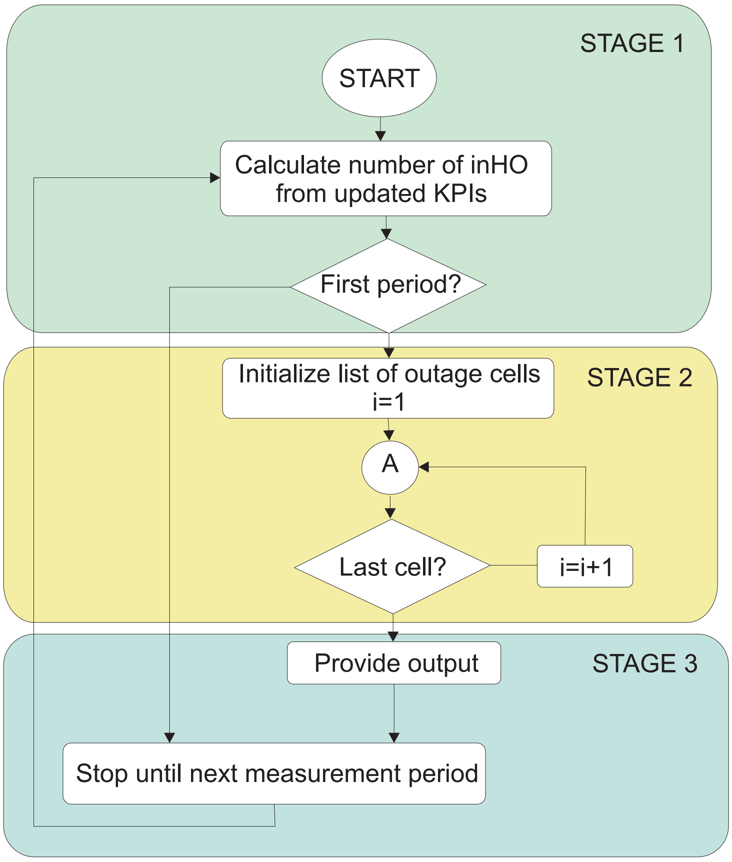

Figure 4.2: Flow diagram of the COD algorithm.

Fig. 4.3 shows a detailed flow diagram of this operation. Firstly, it is checked if the number of inHO in the current *measurement period* is zero and in the previous *measurement period* was not zero (i.e., condition 1). Otherwise, the cell is discarded. In the next steps, a set of rules is applied to determine the final output of the algorithm. Note that the result of the first condition is a set of cells that may be inactive in this *measurement period*. Some of these cells might have been switched off by the operator for maintenance tasks or energy saving reasons. Likewise, some cells might lead to false positives due to very low traffic. In both cases, it is necessary to check if the cell was active from the availability KPIs (i.e., condition 3) to do the final selection. Only the cells that are inactive in the current *measurement period* but have not been switched off by the operator are selected as cells in outage. Finally, it is possible that there are no KPIs available for the evaluated cell. If this is the case, the eNB has been affected by the outage and the related cells do not fulfill the condition 2. The final result of the algorithm indicates the cells that are in outage.

The algorithm can be executed every time that the HO statistics are updated in the OSS (e.g., with a periodicity of 15 minutes or one hour).

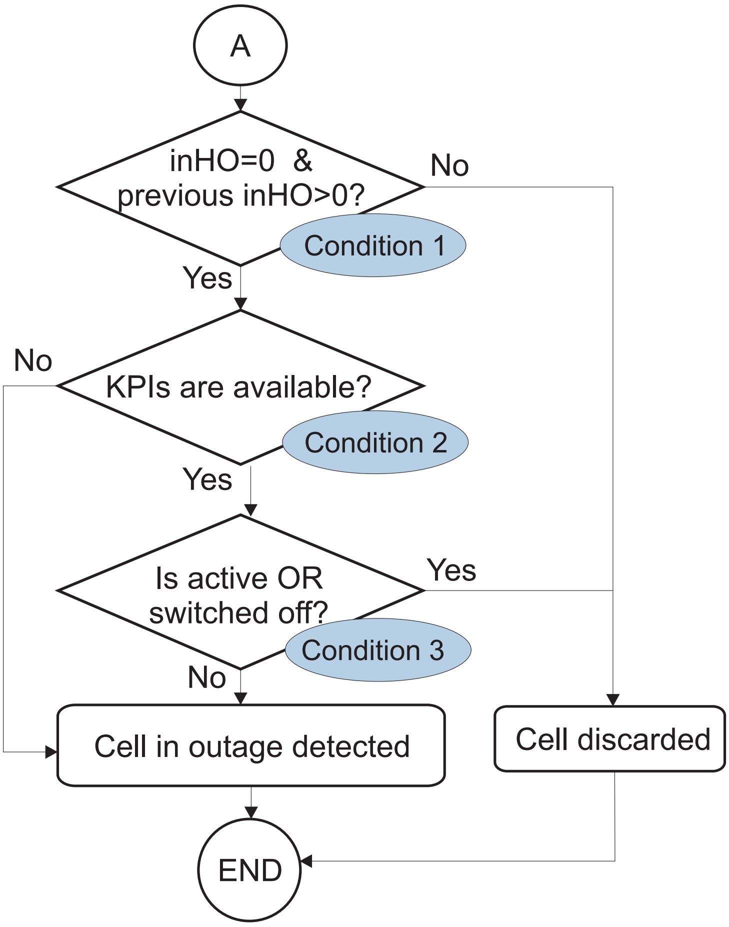

Figure 4.3: Detailed flow diagram of the second stage of the COD algorithm.

4.4 Results analysis

This section presents the results obtained in the COD algorithms analysis. A set of tests is carried out to evaluate the effectiveness of the proposed algorithm and compare it with other approaches. The study is made by using both simulations and real network tests.

COD algorithms tested are:

- COD based on availability KPIs (*Availability KPIs*). This method consists of monitoring the availability KPIs that an eNB sends to the OSS indicating whether a cell is locked due to a problem or it is switched off due to maintenance tasks or energy saving reasons. Only the first case should be considered as outage. The algorithms presented in [27, 28] follow this approach.

- COD based on the lack of KPIs (*Lack of KPIs*). This algorithm tries to detect a possible cell outage by monitoring that the KPIs of each cell are always reported in each measurement period. If there are no KPIs for a certain cell, then the algorithm concludes that the cell is in outage.

- COD based on inHO statistics (*inHO statistics*). This algorithm, described in Section 4.3, is contribution of this thesis.

4.4.1 Simulation tests

The simulation tests are executed using the dynamic LTE system level simulator presented in Chapter 3. This simulator represents the LTE radio access network and allows to estimate the most important KPIs for each cell and adjacency. The Cell Outage Model proposed in Section 4.2 is integrated in this simulator in order to assess the different COD algorithms.

The simulation scenario is a part of a real network consisting of 75 cells. The simulator includes a user mobility model that allows to simulated users with different speeds. The simulator also includes an HO algorithm to generate realistic HO statistics. The HO algorithm considered in this work is based on the A3 event. When the signal level received by a user from a neighboring cell exceeds the signal level received from the serving cell by a margin, HOM, the HO is executed. Table 4.1 summarizes the main configuration parameters of the simulations.

Table 4.1: Simulation parameters

Parameter	Configuration
Cellular layout	75 cells (25 eNBs)
Transmission direction	Downlink
Carrier frequency	2.0 GHz
System bandwidth	1.4 MHz
Propagation model	Okumura-Hata
	Log-normal slow fading, $\sigma_{sf} = 8$ dB
	and correlation distance=50m
Channel model	Multipath fading, ETU model
Mobility model	Random direction, 3, 10, 50 km/h
Base station model	Tri-sectorized antenna, SISO,
	$P_{TX_{max}}$ =43 dBm
Handover	Triggering event = A3
	Measurement type = RSRP
	HOM = 3 dB
Time resolution	100 TTI (100 ms)

In total, 307 outage situations are generated in the simulation: 49 are outages that do not affect the eNB so that KPIs from the cell are available and the related availability KPI indicates the outage situation; and 258 are outages that affect the eNB so that KPIs from the cell are not available in the OSS. In addition, 141 eNB-OSS failed connections have been simulated. The different COD algorithms have been activated during the simulation to assess their effectiveness.

Table 4.2 presents the results in terms of the false positive rate and the false negative rate for each COD method. The false positive rate is the percentage of cases wrongly detected as positive among the total outage cases and the false negative rate is the percentage of undetected cases among the total of normal cases simulated.

Table 4.2: Simulation results

Result	Availability KPIs	Lack of KPIs	inHO statistics
False_Negative_Rate	84%	16%	5.9%
False_Positive_Rate	0%	0.9%	0%

The *Availability KPIs* algorithm obtains 0% of false positives but 84% of false negatives. This value coincides with the frequency of occurrence of the outage cases with the eNB affected because this method cannot detect an outage problem when KPIs are not being reported.

The *Lack of KPIs* algorithm has nonzero false positive and false negative rates. The value of the false negative rate (16%) coincides with the frequency of outages with available KPIs. Moreover, another important disadvantage of this method is that it produces 0.9% of false positives, equal to the frequency of OSS failed connections, since the algorithm identifies every eNB-OSS failed connection as outage.

It is possible to define an algorithm that combines the *Availability KPIs* and the *Lack of KPIs* methods. With this algorithm, the false negatives of both methods can be eliminated. However, this algorithm would have an important number of false positives since the algorithm would classify all the failed eNB-OSS connection situations as cell outages.

Finally, the proposed *inHO statistics* algorithm is able to detect most simulated outages, leading to a low percentage false negatives (5.9%). This situation is related to cells with low traffic so that they should have a small impact on the overall network performance. When a cell with low traffic is in outage, the number of inHO in the current *measurement period* would be equal to zero. The algorithm is able to detect the outage only if the number of inHO in the immediately preceding *measurement period* is nonzero. However, it is possible that the cell does not manage any inHO in the earlier *measurement period* due to the low traffic. In this case, the algorithm cannot detect the outage problem, resulting in a false negative.

The proposed algorithm produces a 0% of false positives, considering the simulated situations, since the availability KPIs allow to detect the potential false positives cases (i.e., cells with very low traffic that have not inHO in a certain *measurement period* although no problems are affecting it). However, in a real network, new situations may occur that produce a false positive, e.g., a cell with no inHO during a certain hour and no KPI available due to an OSS connection failure. Nevertheless, since those situations are not very common, the real percentage of false positives will be very low.

After analyzing the proposed COD algorithm, it is possible to make a comparison with state-of-the-art approaches. Specifically, most COD algorithms found in the literature (e.g., [27, 28]) are based on detecting cells in outage by monitoring KPIs from the cell in outage. All these methods can be represented by the *Availability KPIs* approach in the simulations. The main drawback of these solutions is that they can detect outages only when there are available KPIs from the cell in outage. This situation occurs when the outage does not affect the eNB.

Other state-of-the-art COD algorithms [30, 31] are based on neighboring cell measurements, but user traces are needed to perform these approaches. For this reason, this method is not appropriated for being implemented in real networks since the feature to collect traces is normally disabled.

In [29], a detection algorithm is presented. In this case, detection is done based on neighboring cell measurements. Specifically, the algorithm applies a complex method to conclude if a cell is in outage based on the degradation generated in the cell edge of neighboring cells. The effectiveness of this approach depends on the level of degradation caused by the outage. However, in many situations, it is difficult to appreciate the degradation caused by the outage in the signal quality experienced by the users in the neighboring cells, especially when there is high cell overlapping. To illustrate this, a figure is included below. Fig. 4.4 shows the value of the 50th percentile of the SINR experienced by the users in the neighboring cells of a site in outage. It can be seen that some neighboring cells experience degradation, but others experienced an improvement. In fact, the average value obtained shows a slight increase. Specifically, the average value of the 50th percentile of the SINR in the normal situation is 2.5012 dB and the obtained value in the outage situation is 2.6491 dB. Consequently, although the algorithm proposed in [29] can obtain good results in many situations, this approach has an important limitation to adapt to different scenarios (e.g., scenarios with a high level of overlapping).

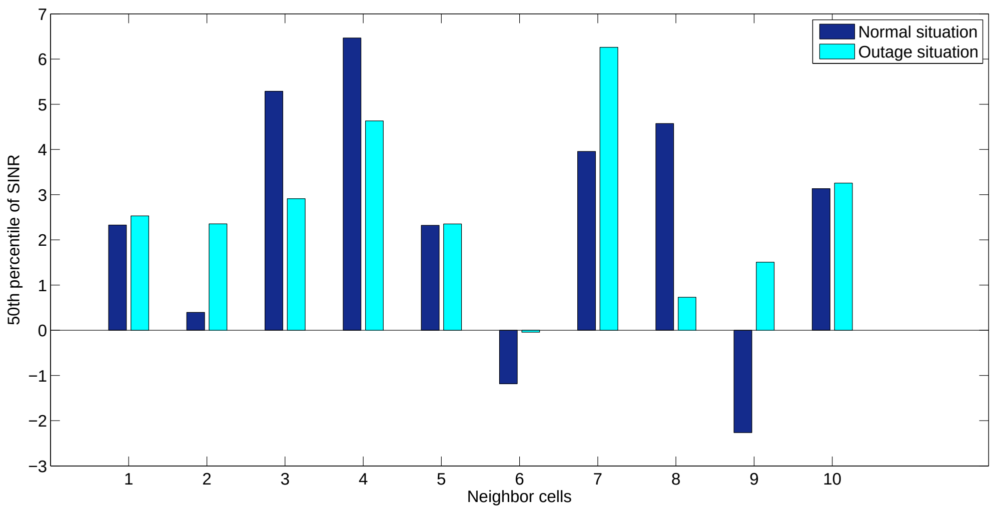

Figure 4.4: 50th percentile of SINR of the neighboring cells of a site in outage.

4.4.2 Real network tests

To complete the analysis of the proposed COD algorithm, a set of tests in a real LTE network is performed. The analyzed network includes approximately 8000 LTE cells. The COD methods under study have been active during 9 days and executed every hour, which is the periodicity of KPIs updating in the OSS.

Table 4.3 shows the results of the analysis representing the average number of cell outages detected per day.

Table 4.3: Average number of cell outages per day in a real network

Availability KPIs	Lack of KPIs	inHO statistics
15.78	50.1	25.2

The number of cell outages detected by the *Availability KPIs* method is the lowest. Since this algorithm is not able to detect outages affecting the eNB, the false negative rate may be very high.

The *Lack of KPIs* method only detects the outages that affect the eNB. The number of false positives may be high, since the eNB-OSS failed connections are detected as outage problems. This method only detects outage problems affecting the whole site, and cannot detect the outage cases that affect only a single cell.

The results shown in Table 4.3 for the proposed *inHO statistics* algorithm is the total number of cell outages (i.e., the final output of the algorithm). Table 4.4 shows the results for each algorithm stage for one of the nine analyzed days. This method leads to a high number of candidate cells in outage as a result of the first condition (i.e., condition 1). The reason for this is that this algorithm detects all the cells that seem to be inactive in the current *measurement period* (i.e., cells with inHO equal to zero). This result may include cells that are in outage, cells that have been switched off and cells with a very low traffic. If a cell has a problem with the eNB-OSS connection but does not have problems to serve traffic, then this cell is not detected as faulty (the algorithm does not have the same false positives as the *Lack of KPIs* method). By checking the availability KPIs, it is possible to remove those cells that have been manually switched off and the active cells from the final solution, thus eliminating most of the potential false positives of the algorithm.

Table 4.4: inHO statistics algorithm results

Parameter	Results
Candidate cells	2271
Active cells (potential false positives)	2220
Switched off cells	32
Final output (cells in outage)	19

As described in Section 4.4.1, some situations may produce false positives in the proposed method so that the false positive rate of the algorithm is the probability of occurrence of these situations (e.g., a cell with no inHO during a certain hour and no KPI is available due to an OSS connection failure). Nevertheless, this type of situations are not common in a real network.

The proposed algorithm may present a nonzero false negative rate. If a cell does not carry traffic during some hours and has an outage at this moment, the algorithm cannot detect it because the number of inHO in the previous *measurement period* is equal to zero. It is important to point out that this limitation only affects cells with very low traffic that do not have a significant impact on the overall network performance. Another false negative situation is when a cell suffers outages whose duration is less than the algorithm execution period. Hence, the false negative rate of the proposed algorithm can be calculated as the probability of occurrence of outages in a cell with no traffic and outages with a duration less than the algorithm execution period.

Most detected cell outages are problems that have lasted a few hours but there are some cases of outage that have affected a cell during many hours even days. The detected cases have been confirmed by the operator.

Fig. 4.5 - 4.8 illustrate how the algorithm works. All figures show the value of three KPIs for a certain cell during a day. The selected KPIs are the number of connections, the inactivity time indicating the number of seconds per hour that the cell has been inactive and the number of inHO. Firstly, Fig. 4.5 shows an outage case that does not affect the eNB. In this situation, there are KPIs available from the cell in outage. It can be seen that, when the number of inHO becomes zero, the availability KPI (i.e., inactive time) indicates that the cell is not active for the whole hour (3600 s). At the same time, the number of connections in that cell becomes zero too.

Fig. 4.6 presents the behavior of the KPIs when a cell is in outage and there are no KPIs available. In this situation, the only way to detect the outage is using the number of inHO.

The last two figures represent situations when no outages affect the network. In Fig. 4.7, a potential false positive situation is shown (hour 14), when the number of inHO becomes zero. in the absence of availability KPIs, this would indicate that the cell is in outage. However, the availability KPI shows that the cell has not been inactive at any time. Moreover, the figure shows that the cell is carrying traffic during all day. Such information is used by the proposed algorithm to discard this as a cell outage. The last figure, Fig. 4.8, presents the case of an eNB-OSS connection failure. It is observed that there are some hours with no KPIs available from the cell (i.e., number of connections and availability KPI are not available at certain hours). However, it is still possible to collect the number of inHO at these hours, since it is calculated based on neighbor measurements. This indicator shows that the considered cell has a nonzero number of inHO, which is clear indication that the cell is carrying traffic and does not have an outage problem.

4.5 Conclusions

A COD algorithm has been proposed in this chapter. The algorithm is based on the number of inHO, which is available as a counter in the network management system. The algorithm allows to detect a cell outage even when KPIs from the considered cell are not available. A set of simulations and real network tests have been carried out to evaluate the proposed detection method. Results show that, unlike previous approaches, the proposed algorithm is able to detect most outage situations in a real network. The main limitation of the algorithm is that the cell outages that affect cells with very low traffic cannot be detected. However, these outage

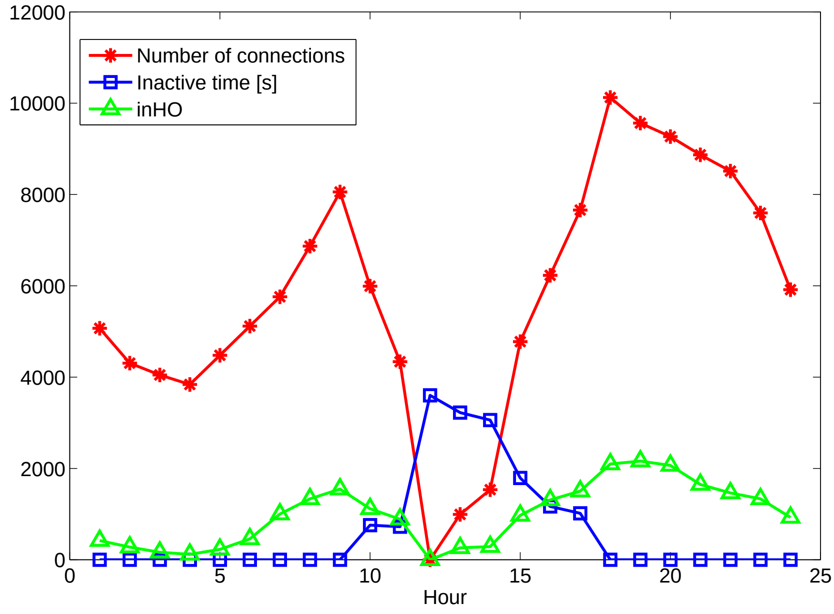

Figure 4.5: Cell in outage with available KPIs.

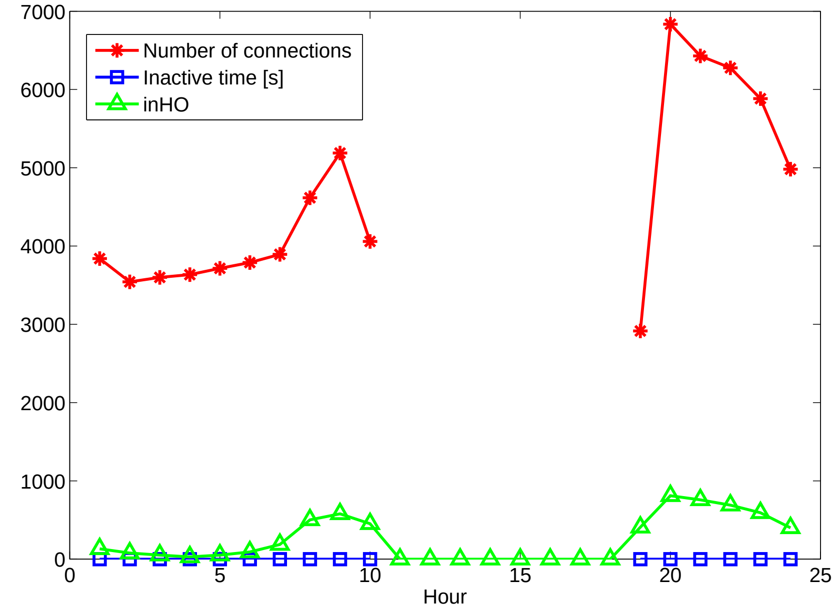

Figure 4.6: Cell in outage with no KPI available.

situations would affect a small population and would thus have a low impact on the overall network performance.

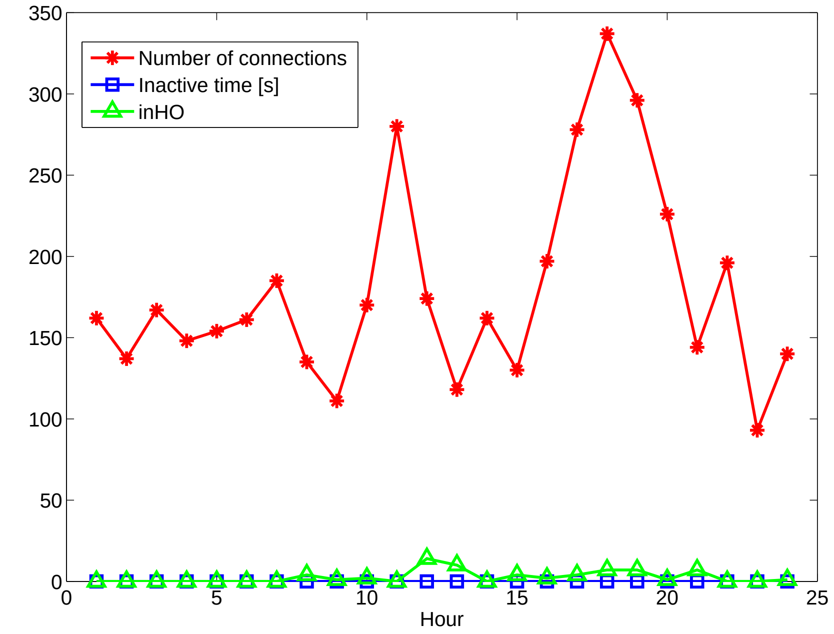

Figure 4.7: Cell without problems.

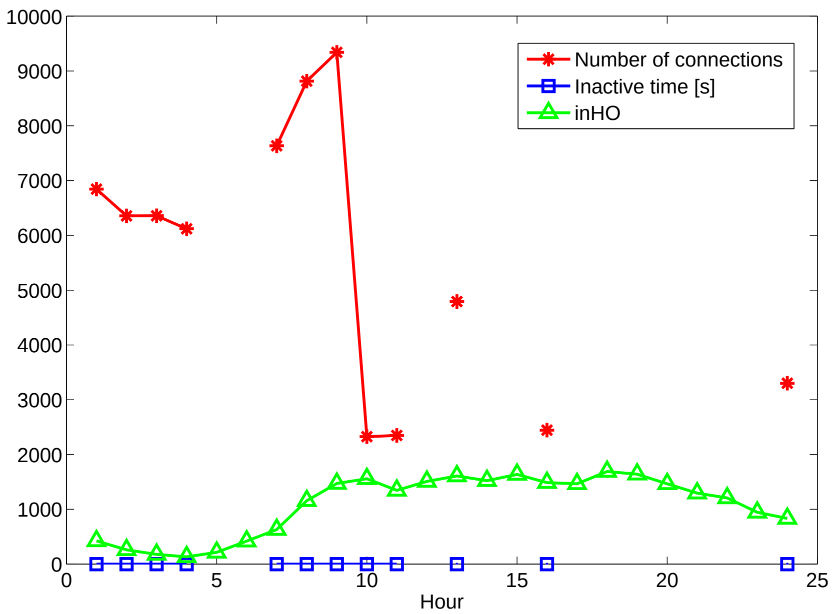

Figure 4.8: eNB-OSS connection failure.

Chapter 5

Cell Outage Compensation

This chapter is devoted to the COC methodology. The proposed COC scheme presents an important improvement of the COC function by adapting different COC strategies to different cell outage situations. For this purpose, a detailed analysis of the faulty situation is first carried out to classify the degradation produced by the cell outage in the neighboring cells. Then, a different COC algorithm is applied to each affected neighboring cell. In addition, some COC algorithms based on changing HO parameters are presented.

The chapter is organized as follows. Section 5.1 introduces the related work. Section 5.2 presents the first phase of the COC methodology, namely the cell outage analysis. Three methods are described to classify outages depending on the degraded metrics in neighboring cells. In addition, a method for estimating the lost traffic due to a cell outage is proposed to quantify the load that cannot be absorbed by neighboring cells. Section 5.3 presents the study of new COC algorithms that can be adapted to the specific outage problem. Finally, Section 5.4 summarizes the conclusions.

5.1 Related work

Most Self-Healing use cases defined by the 3GPP [9] are related to the COM. This function is composed of COD and COC. The COD function aims to detect the problematic situation, while COC aims to reduce the degradation caused by a failure in a cell until the fault is solved. The compensation can be made by modifying different configuration parameters in the network. Such parameters usually belong to the neighboring cells. All the modifications carried out by the compensation algorithm must be reverted when the network failure is solved. Several works that cope with these two issues can be found in the literature. As for the COD functionality, Chapter 4 includes a detailed analysis of the state-of-the-art related to this function.

In the literature, a major difference between different COC algorithms is the control parameter used for the compensation action. Thus, the main control parameters presented in the literature are: antenna tilt ([33, 34]), uplink target received power level (P0) ([33, 35]), RS power ([33, 37]) and transmission power of the base stations ([36]). It is important to point out that operators usually are unwilling to modify the transmission power of the base stations, since these changes may produce coverage holes. Specifically, in [33], the authors evaluate the tunning of different parameters (i.e., reference signal power, P0 and antenna tilt) and analyze their effectiveness in different scenarios. In that study, the cell outage causes a coverage hole, but the compensation can be made focusing on improving coverage or throughput. The obtained results show that tunning P0 and antenna tilt are the most effective strategies in improving coverage, while P0 is the most effective in improving throughput. The objective in [34] is to increase the coverage area of the compensating cells in the outage area. Parameter changes are based on propagation measurements. The COC algorithm presented in [35] improves the coverage and signal quality in the outage area. The authors of [36] apply a COC algorithm to an irregular network (i.e., cellular network where base station locations, power levels and coverage areas are highly inhomogeneous). Finally, a distributed COC algorithm is presented in [37]. Compared to centralized schemes, the distributed algorithm can enhance management efficiency and remain active when the management node fails.

It is also possible to find in the literature compensation methods that modify more than one parameter at the same time. In [38, 41], an algorithm for compensating an outage by simultaneously modifying the antenna tilt and the transmission power of the base station based on reinforcement learning is proposed. In [38], the authors present a comparison between the modification of both parameters and the compensation using each parameter separately. As expected, the conclusion is that the method that combines both parameters obtains the best results. In [41], the compensation algorithm is applied to a heterogeneous network. The same set of configuration parameters is used by the authors of [40] that present a COC algorithm based on fuzzy logic.

There are also other works that implement COC algorithms applied to different technologies. In [39], the authors present a fuzzy logic algorithm that compensates outage problems by modifying the transmission power of several access points in a Wireless Local Area Network (WLAN).

In addition to the previous works, some authors propose to apply Coverage and Capacity Optimization (CCO) algorithms to cell outage problems. In most cases, the modified parameter is the antenna tilt [42, 43, 44, 45]. The authors of [42] present an algorithm with two phases. The objective of the first phase is the antenna tilt optimization. In the second phase the antenna tilt is fine-tuned to adapt to network dynamics such as the failure of a neighboring cell. In [43], different strategies based on reinforcement learning are proposed. Each proposed strategy is analyzed in different network situations: deployment, normal operation and cell outage. The authors of [44] present a heuristic variant of the gradient ascent method that allows to optimize the antenna tilt even in a cell outage situation. Finally, there are other works that simultaneously modify more than one parameter in order to improve the results. For instance, in [45], an optimization method based on the joint modification of antenna tilt and a cell reselection offset is proposed.

All previous approaches present an important limitation. These works assume that the main effect produced by the cell outage is a coverage hole and they do not consider other possible effects, such as congestion or mobility problems. Consequently, most state-of-the-art COC algorithms aim to cover the outage area by increasing the coverage area of the neighboring cells by modifying the antenna tilt or the transmission power of the base stations. However, in some network conditions, a cell outage problem may not lead to a coverage hole. Consequently, the above COC algorithms may not compensate the caused degradation.

5.2 Improving Cell Outage Management through data analysis

This section is organized as follows. Section 5.2.1 introduces the problem formulation. Section 5.2.2 describes the proposed methods for cell outages analysis. The proposed method for estimating the lost traffic due to a cell outage is presented in Section 5.2.3. Finally, some guidelines to improve the existing COC mechanisms are included in Section 5.2.4.

5.2.1 Problem formulation

Before determining the overall impact of a cell outage, an accurate detection of this event is required. This is carried out by the COD functionality [27, 41]. In general, by monitoring alarms and KPIs from each cell it is possible to detect most cell outages. However, there are some particular cases where KPIs are not available, but the cell is still alive. In these cases, extra information such as neighbor cell lists or HO-related data is needed to discriminate both cases. For example, in the algorithm described in Chapter 4 when the number of inHO measured in neighboring cells becomes zero, the cell under study is likely to be in outage.

Once cell outages are detected, a powerful COC scheme should distinguish between outage situations by analyzing the impact on neighboring cells. This is justified by the fact that some cases will require more attention than others from the operator perspective. For example, depending on the amount of traffic absorbed in the affected area, neighboring cells could become overloaded or not. A slight increase in the traffic of neighboring cells may happen in deployments with high cell densification or in areas with low offered traffic. In addition, in early deployment stages, a cell outage may produce important coverage holes which would negatively impact on user accessibility and retainability. In contrast, in mature deployments, the new scenario after a cell outage may lead to mobility problems in neighboring cells, especially between those with overlapped coverage areas. Moreover, the type of scenario may determine the effects caused by a cell outage, so that it is important to consider the type of affected cells (e.g., if the cell outage occurs in a heterogeneous network). Thus, it is clear that the same failure (i.e., a cell outage) may produce different effects in neighboring cells that should be compensated in a different way.

Fig. 5.1 shows the effects produced in two different neighboring cells by the same cell outage. Specifically, the figure shows KPIs related to traffic (no. of connections), bad coverage (no. of measurements with RSRP level below a certain threshold) and cell load (Computer Processing Unit (CPU) processing load) for the two selected neighboring cells on an hourly basis. It can be seen that the cell outage that occurs in hours 59-62 produces a degradation in the coverage and an increase in traffic Neighbor 1, whereas Neighbor 2 suffers a congestion problem. In this situation, a COC strategy based on changing antenna tilt can improve the bad coverage issue in Neighbor 1 but would fail to solve the effect on processing load in Neighbor 2.

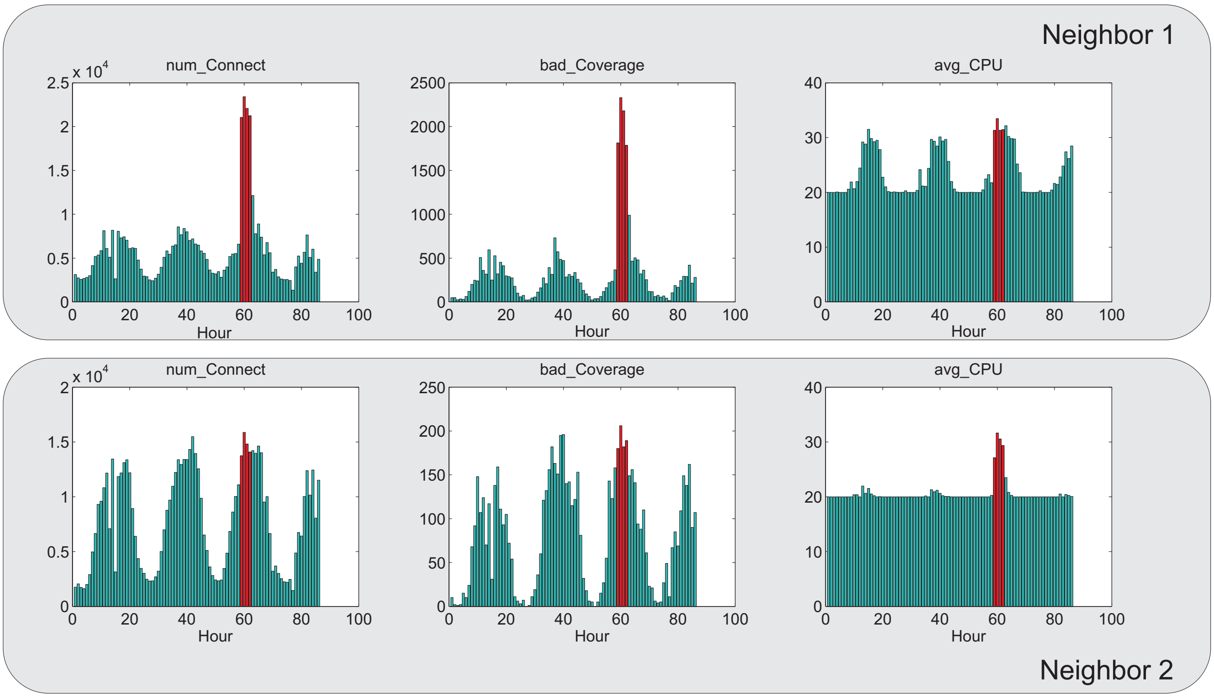

Figure 5.1: Degraded KPIs from two neighboring cells in case of cell outage.

In this section, an analysis of cell outages based on identifying degraded KPIs in neighboring cells is presented. In a first (offline) approach, a method for analyzing historical records of cell outages is proposed. Then, various methods to analyze cell outages in a real-time (online) SON manner are presented and evaluated taking the offline approach as a baseline.

5.2.2 Analysis of cell outages

Offline analysis method

In Self-Healing, a common technique to manage anomalies in the network is to study the correlation between different metrics, such as alarms or KPIs. In particular, several works using the correlation for COD algorithms can be found in the state-of-the-art [85, 86]. The basis of these algorithms is the recognition of the characteristic behavior of faults by correlating the KPIs with each other. However, in this work, the correlation is not used to detect cell outages, which is done by the COD algorithm explained in Chapter 4. Alternatively, the correlation is used to analyze the effects produced by the cell outage in the neighboring cells. Since the cell outage is a special fault where KPIs from the problematic cell are lost, the analysis of KPIs must necessarily be performed in neighboring cells.

The first step in correlation-based Self-Healing is the selection of metrics to be correlated. This information should be as complete as possible, covering different aspects of the network (e.g., coverage, signal quality, capacity, etc.). A representative set of KPIs to analyze degradation in cell outages is the following:

- *num_ Connect* : it measures the number of established connections in a cell at network layer, so that it is an estimation of the carried traffic.
- *bad_ Coverage*: it is based on the number of UE reports indicating a low signal level received from the serving cell. A high value means that there is a lack of coverage in that cell.
- *inter_ RAT_ HO*: it reflects the number of calls that have executed an HO to another cell belonging to a different radio access technology (RAT). This may reveal, for example, a lack of coverage in a certain RAT.
- *HO_ PP*: it measures the number of HO ping-pong events per cell produced in the network. As a consequence of a wrong configuration of mobility parameters, an HO ping-pong event occurs when the same user experiences two (or more) consequtive HOs that take place between the source and the target eNB and vice versa. This problem may significantly decrease the performance of HOs, while increasing network signaling load unnecessarily.
- *avg_ RSSI*: this KPI calculates the average value of the RSSI, which reflects the received power level including not only the desired signal but also background noise and interference.
- *avg_ CPU_ Load*: it measures the average load of the CPU in the eNB. This KPI may indicate hardware congestion.
- *num_ Drops*: it counts the number of dropped calls in a cell as an indication of user retainability problems.
- *Failed_ Conn_ Estab*: it measures the number of failed connection establishments as an indication of user accessibility problems.

The above KPIs are currently measured on an hourly basis by the OSS. In the proposed method the time evolution of these metrics is used to find potential degradations on neighboring cells due to the impact of cell outages occurred in the network. The procedure to detect KPI degradations is shown in Fig. 5.2, where it is assumed that the duration of cell outages is only a few hours for clarity. The aim of the proposed algorithm is to generate a set of reference signals for each analyzed KPI that includes a certain level of degradation independently of the real values of the KPI. These estimated signals will be compared to the current values of the KPI to determine if there are degradations due to the outage. The algorithm is divided in four phases:

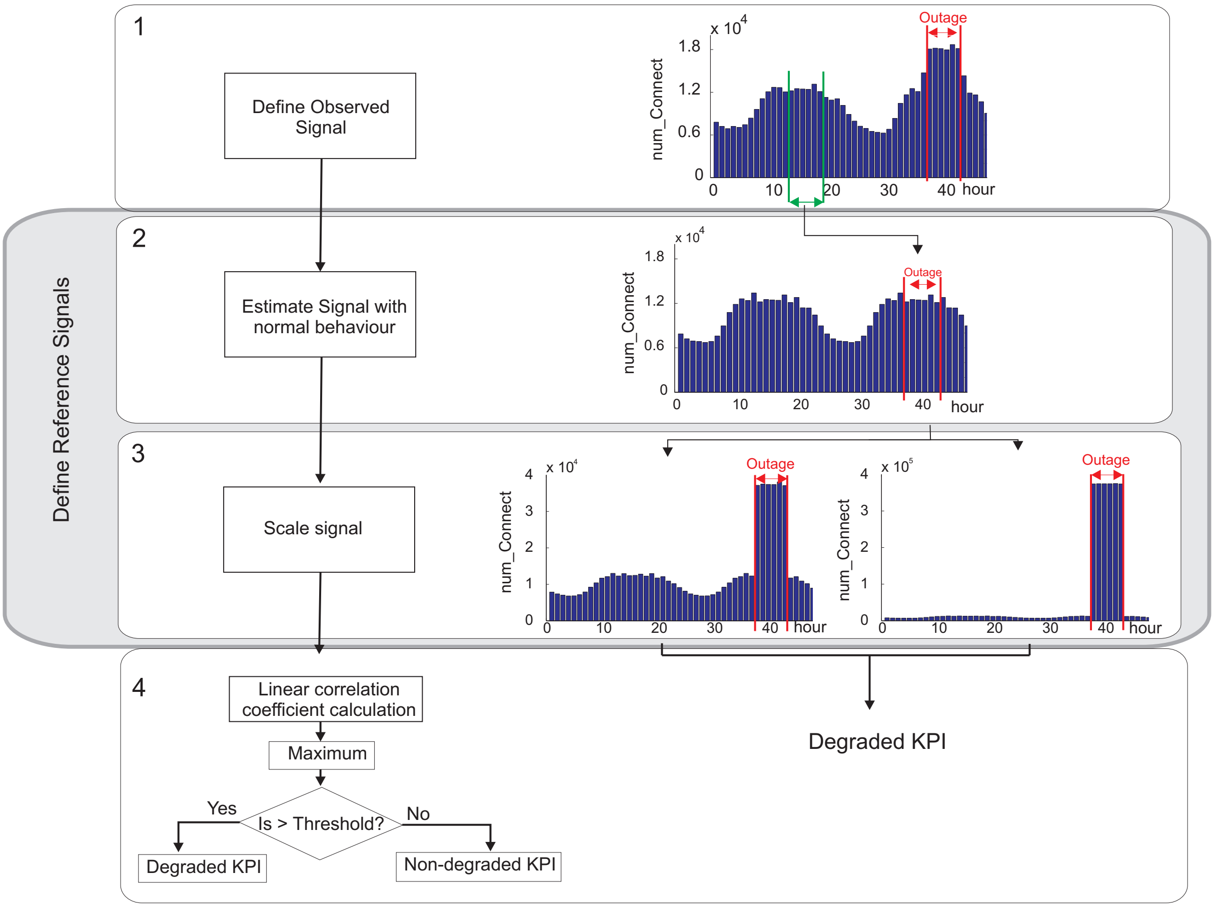

Figure 5.2: Flow diagram of the proposed cell outage analysis method.

1 *Define Observed Signal.* For each neighboring cell, a set of samples of each KPI in a period of two days is collected. One day should comprise the cell outage and the other day should not include any outage.

2 *Estimate signal with normal behavior.* The previous signal is modified in order to generate a signal with no effects due to the cell outage. For this purpose, the samples that fall within the cell outage interval are substituted by samples at the same hours of the other day. These samples should not be affected by the cell outage.

3 *Scale signal.* The samples at the hours of the cell outage are scaled to simulate a possible degradation produced by the outage. In particular, two different scaling factors (e.g., 3 and 30) are applied to cover both slight and strong degradations. The resulting signals are the reference signals.

4 *Calculate correlation.* The linear correlation coefficient is calculated between the observed and the reference signals. This is made for each scaling factor. The maximum correlation value for the used scaling factors is selected. If the correlation value is above a specific threshold (e.g., 0.80), the KPI of the analyzed neighboring cell is considered to be degraded by the cell outage.

The time needed to complete the phases above is negligible compared to the KPI reporting period (typically, 1 hour), so that this analysis does not increase significantly the reaction time of the compensation process.

In the proposed algorithm, the length of the signals has been carefully selected, since the correlation values are very sensitive to this parameter. More specifically, the time length of the signals should be consistent with the duration of cell outages. For example, an excessive time length of the signals compared to the duration of cell outages could mask the impact of the cell outage on the correlation values. Another issue is related to the selection of days in the step 1 of the algorithm. Depending on the day of the week, the traffic pattern may be different, especially between business days and weekend. Since hours at different days are correlated, the selected days of the week should also be consistent in relation to the traffic pattern. To avoid such an issue, in this work, only time intervals during the business days have been analyzed.

The above-described algorithm has been applied to 22 real cases of LTE macro cell outages. The selected dataset corresponds to an LTE network composed of 8000 cells approximately. The information about different KPIs is collected every hour. The inputs of the algorithm are the above mentioned KPIs, which are measured in the neighboring cells of each cell in outage. To consider a cell as neighbor, the number of HOs between both cells must be higher than zero. To simplify the analysis, only the three most degraded neighboring cells (i.e., those with higher number of degraded KPIs) are selected. In Fig. 5.3, a histogram of the different degraded patterns that have been found in neighboring cells is depicted. As observed, the most repeated pattern (i.e., pattern 1) is the one without any degradation in the KPIs. This reveals that in many cases cell outages only have an impact on none, one or two neighboring cells. Pattern 2 is given by the degradation in *num_ Connect* and *bad_ Coverage*, which are the typical effects of cell outages in traditional single-RAT networks, i.e., an increase of traffic in neighboring cells and the creation of a coverage hole (reflected in a bad coverage statistics). One of the most repeated patterns, pattern 4, is given by a degradation only in *HO_ PP*. This may be common in networks with a high degree of cell overlapping. In these cases, a cell outage may lead to a situation of a lack of dominant cell, where the number of unnecessary HOs would be increased. Pattern 5 presents a typical situation of multi-RAT networks, where the traffic can be mainly absorbed by other RATs (especially if cells are co-sited), impacting on *Inter_ RAT_ HO* rather than on *num_ Connect* in the neighboring cell. Patterns 3 and 6 are subcategories of pattern 2, which are typical effects of cell outages, as previously mentioned.

As the impact of a cell outage on neighboring cells becomes more severe, the number of degraded KPIs is also higher. An example of this is represented by patterns 11, 13, 23, 24, 26 and 27. In these cases, a coverage hole is created affecting both *bad_ Coverage* and *Inter_ RAT_ HO*. In addition, a significant amount of traffic is absorbed by the neighboring cells so that *num_ Connect* is increased. The coverage hole and the increased traffic in neighboring cells raises the likelihood of call dropping, which is illustrated by the increase in *num_ Drops*. In some cases (see patterns 18, 24 and 26), the cell outage forces neighboring cells to carry an excessive amount of traffic, so that user accessibility is deteriorated. As a result, both *Failed_ Conn_ Estab* and *num_ Connect* will be affected. Most of the remaining patterns are combinations of the previously analyzed

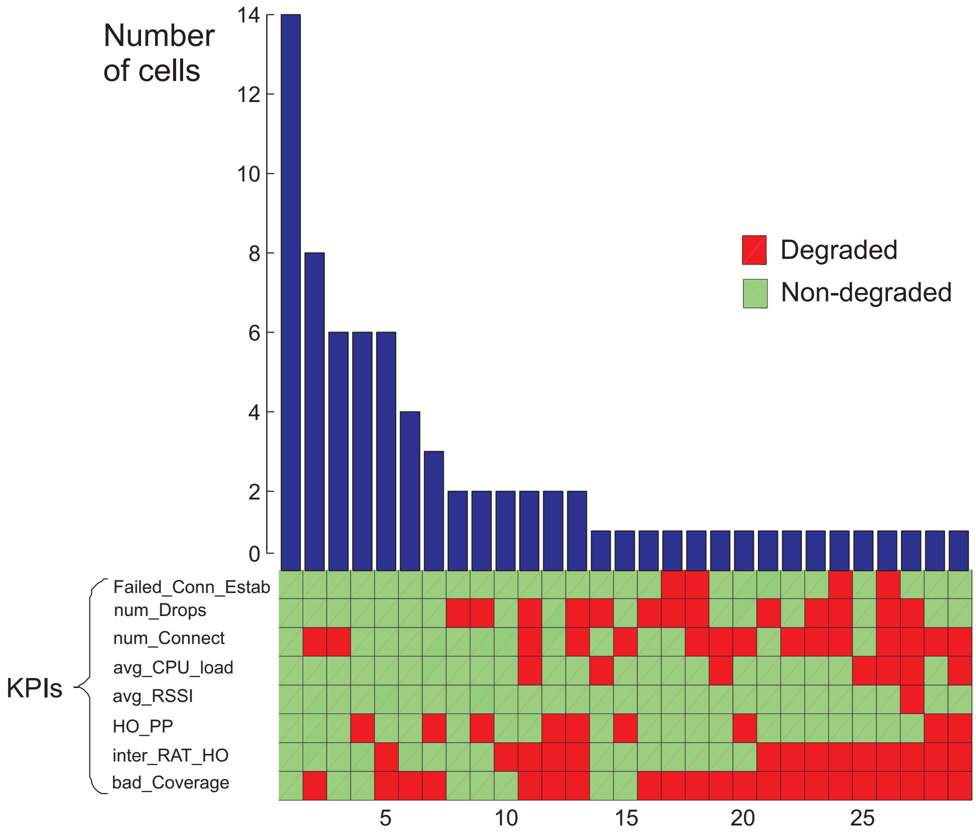

Figure 5.3: Detected degradation patterns after outage and number of occurrences.

cases. Cell outages causing interference problems in the downlink are more unusual, thus the *avg_ RSSI* is rarely affected (see pattern 27).

Online analysis method

It is clear that the higher the number of available data samples under cell outages, the more accurate the analysis should be. However, in a SON context, cell outages occur at the same time they have to be analyzed. Such a constraint calls for a fast analysis method to reduce traffic losses. In addition, the effectiveness of the compensating actions depends on the success of the analysis. In this section, the proposed algorithm analyzes the cell outage immediately after the detection, so that in general only one sample of the cell outage is available. In particular, two online methods to analyze outage effects have been designed, differing in the way that KPI degradations are determined:

- *Corr_ online*: this method calculates the correlation between the observed signal and a reference signal (different from that used in the offline method) which is defined as the unit step function with the jump discontinuity corresponding to the first hour of the cell outage. In this thesis, the Pearson correlation coefficient, r, is used, which is defined as

$$r = \frac{N\sum xy - \left(\sum x\right)\left(\sum y\right)}{\sqrt{\left[N\sum x^2 - \left(\sum x\right)^2\right]\left[N\sum y^2 - \left(\sum y\right)^2\right]}}, \tag{5.1}$$

where x is the original signal representing the time evolution of a certain KPI, y is the reference signal and N is the number of samples considered for both signals. If the correlation value is above a threshold, the KPI is considered to be degraded. Conceptually, the reference signal represents the cell availability along time. In addition, the length of the signals is shorter than in the offline approach. In particular, only 6 samples are considered: the first 5 samples are not affected by the outage and the last sample corresponds to the first hour of the cell outage.

- *Delta_online*: in this method, a threshold (thr) is determined as a function, shown in eq. 5.2, of the average (avg) and the standard deviation (std) of the KPIs under normal circumstances. Then, the sample measured under the cell outage is compared to this threshold in order to determine whether the KPI is degraded or not.

$$thr = 2\frac{avg}{std} \tag{5.2}$$

The evaluation of these methods has been carried out with the same dataset as in the offline analysis, which is taken as the baseline. Results are shown in Table 5.1, where the second column shows the analysis success rate measured as the number of neighboring cells correctly analyzed divided by the total number of cases. A neighboring cell is successfully analyzed if all their KPIs are correctly identified as degraded or not degraded according to the offline approach. As observed, both methods have similar good performance (above 80% success rate). Thus, these algorithms can be part of effective SON algorithms that quickly reacts to cell outages.

For comparison purposes, Table 5.1 also includes the result obtained with a simple method based on the relative increases of KPIs. This method is similar to that used by operators for the analysis of faults. In this case, a KPI is identified as degraded if the relative increase measured is higher than a threshold. Results show that the proposed methods obtain higher success rate.

Table 5.1: Effectiveness of online classification methods for outage consequences

Method	Success rate (%)
Corr_online	81.83
Delta_online	83.17
Relative increase	76.5

5.2.3 Measuring the load impact on neighboring cells

After a cell outage, the offered traffic in the affected area should be absorbed as much as possible by neighboring cells in the same RAT or another RAT that provides similar quality of service.

Depending on the particular conditions of each cell outage, the amount of traffic that is lost

or steered towards a sub-optimal RAT may be different. In this sense, a neighboring cell with a very large overlapped coverage area (e.g., a secondary carrier frequency) is more likely to absorb a larger amount of traffic than cells with separate coverage areas. In the first situation,

the compensating actions of the involved cells should be more conservative, since the problem has already been partially mitigated. In the second case, the compensating actions should be carried out by cells with partial or limited overlapping coverage areas, so that changes in radio parameters need to be larger. Thus, an estimation of the lost traffic can be essential to conduct more rational compensating actions. In this thesis, the lost traffic is estimated from KPIs measured in neighboring cells. In particular, the metric *Lost_ Traffic_ Rate* is calculated as an estimate of the actual lost traffic divided by the total traffic that would be carried by the outage cell in normal conditions. The procedure to calculate this metric is as follows:

- First, the total traffic (i.e., trf_{total}) that would be lost if no traffic was absorbed by neighboring cells is obtained by aggregating the *num_ Connect* samples at the outage hours on another day, assuming that the traffic carried during these hours is the same. The calculation can be expressed as:

$$trf_{total} = \sum_{hour=h_{min}}^{h_{max}} num\_Connect(outage\_cell, normal\_day, hour)\,, \tag{5.3}$$

  where h_{min} and h_{max} are the initial and final hours of the outage on a normal day, respectively. This term is equivalent to the denominator value of *Lost_ Traffic_ Rate*.

- Then, the lost traffic (i.e., trf_{lost}) is estimated by subtracting the traffic absorbed by neighboring cells from the previous term. For this purpose, the traffic absorbed by each neighboring cell is computed as the difference in *num_ Connect* between the outage hours and the same hours on a normal day, measured in the neighboring cell. Note that the absorbed traffic may lead to call dropping due to bad radio conditions or congestion. For this reason, the *num_ Drops* in the neighboring cell must be considered. In particular, the difference in *num_ Drops* between the outage hours and the same hours on another day is subtracted from the absorbed traffic to provide a more realistic approximation. In addition, only the main neighboring cells with a positive value of absorbed traffic should be included in the formula:

$$
\begin{aligned}
trf_{lost} = trf_{total} - \sum_{nbr \in N_{outage\_cell}} \Bigg[\Bigg(& \sum_{hour=h_{min}}^{h_{max}} num\_Connect(nbr, outage\_day, hour) \\
& - \sum_{hour=h_{min}}^{h_{max}} num\_Connect(nbr, normal\_day, hour) \Bigg) \\
& - \Bigg(\sum_{hour=h_{min}}^{h_{max}} num\_Drops(nbr, outage\_day, hour) \\
& - \sum_{hour=h_{min}}^{h_{max}} num\_Drops(nbr, normal\_day, hour) \Bigg) \Bigg] ,
\end{aligned} \tag{5.4}
$$

where N_{outage_cell} is the set of neighboring cells of the cell in outage and h_{min} and h_{max} are the initial and final hours of the outage, respectively.

- Finally, the previous term is divided by the total traffic calculated in the first step:

$$
Lost\_Traffic\_Rate = \frac{trf_{lost}}{trf_{total}} . \tag{5.5}
$$

To be consistent, the obtained value is limited to the range between 0 and 1, meaning that the traffic may be totally absorbed or lost by neighboring cells, respectively.

Fig. 5.4 presents the *Lost_ Traffic_ Rate* together with the degraded KPIs of each neighboring cell in the same dataset used in Section 5.2.2. Note that the neighboring cells affected by the same cell outage share the same value of *Lost_ Traffic_ Rate*, since this indicator is related to the cell in outage. As expected, when the impact on KPIs in neighboring cells is none or marginal (i.e., the left part of the figure), the amount of lost traffic is high. Roughly, the higher the number of degraded KPIs, the larger the amount of traffic is expected to be absorbed by neighboring cells. When *num_ Connect* and *num_ Drops* KPIs are affected, the involvement of neighboring cells in the absorption of traffic is especially important. In addition, when the *avg_ CPU_ Load* is also degraded, the amount of traffic absorbed by neighboring cells can be even larger, causing important problems in those cells. However, there are some cases where these assumptions cannot be applied. In particular, some neighboring cells (e.g., patterns 57 and 59) present a non-degraded *num_ Connect* and *num_ Drops*, but the absorbed traffic is higher than expected.

By combining the information provided by the degraded KPIs and lost traffic, the strength of the compensating actions can be better adapted to the specific cell outage.

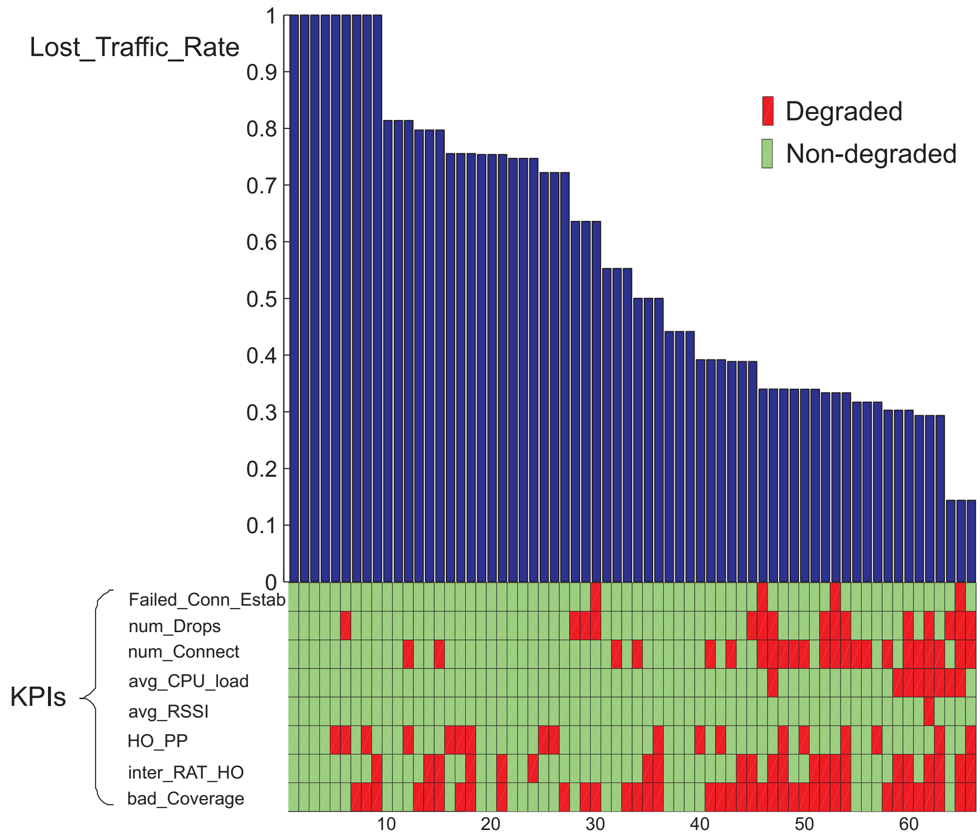

Figure 5.4: *Lost_ Traffic_ Rate* for each selected neighboring cell.

5.2.4 Developing advanced Cell Outage Compensation algorithms

This section discusses some guidelines to improve the existing COC mechanisms by applying cell data analysis. In particular, the proposed structure of COC algorithms should comprise the following phases:

- *Neighboring cell selection*: this stage can be understood as a filter by which neighboring cells are pre-selected to participate in the COC, while the particular role played by each cell will be determined in next stages. The information used to select the most appropriate cells can be related to the network layout (e.g., the degree of overlapping between coverage areas, the location of nodes) or mobility (e.g., based on the number of HO events).

- *Radio parameter selection*: the common effect of cell outages in traditional networks is a coverage hole, which has been typically compensated by uptilting the antenna in neighboring cells. However, if the cell outage involves a lower degree of lost traffic, which has been partially absorbed by the neighboring cells, the antenna tilt should not be adjusted to absorb more traffic. In addition, each cell outage may result in different kinds of degraded KPI patterns that should be compensated in a different way. Table 5.2 summarizes different compensation approaches depending on the degraded KPI. In particular, a high value of *HO_ PP* indicating a waste of radio signaling resources can be mitigated by a proper configuration of the hysteresis parameter. A high value of *inter_ RAT_ HO* would indicate that many calls are being steered to another RAT (e.g., UMTS), where users may experience poor performance. In this case, the inter-RAT HOM should also be adjusted to steer traffic in a more effective way. A degradation of *Avg_ CPU_ Load* may involve congestion. In this case, the traffic load of the neighboring cell should be balanced with respect to other neighboring cells by modifying the intra-RAT HOM parameter.

Table 5.2: Radio parameter selection for outage compensation

Degraded KPI	Parameter for COC
bad_ Coverage	Tilt
HO_ PP	HO hysteresis
inter_ RAT_ HO	inter_RAT HOM
Avg_ CPU_ Load	intra_RAT HOM

- *Determining the magnitude of the compensating action*: in general, SON functionalities progressively adjust radio parameters in order to accomplish a specific goal, which is typically reaching certain KPI levels. If current values are far from the desired levels, then the actions should be more aggressive, i.e., larger magnitudes of changes are needed. In COC algorithms, parameter changes in neighboring cells can be modulated according to some data analysis. As explained in Section 5.2.3, estimating the traffic loss in the affected area becomes a key factor to determine the strength of the COC actions to modify the radio parameters, especially the antenna tilt. For instance, if most traffic is absorbed by the neighboring cells, then slighter compensating actions will be required and vice versa.
- *Control of parameter changes*: the last part of the COC algorithm is given by the gradual modification of the selected radio parameters until either the stationary state is reached, or the outage cell is recovered. In any case, once the outage cell is recovered, the parameter configuration should be reverted.

5.3 Adaptive Cell Outage Compensation in Self-Organizing Networks

This section is organized as follows. Section 5.3.1 presents the problem formulation. Section 5.3.2 describes the system model including the considered control parameters and system measurements. Section 5.3.3 is devoted to the proposed COC methodology and presents the proposed COC algorithms. Finally, results and conclusions are included in Sections 5.3.4 and 5.4, respectively.

5.3.1 Problem formulation

When a cell is in outage, it cannot carry traffic. Therefore, the first effect of a cell outage is that users in the coverage area of the faulty cell lose their connection. However, depending on network conditions, different situations may occur in the problematic area. In some cases, when the level of overlapping between the neighboring cells is low, the cell outage may produce a coverage hole. Affected users can only recover their connection if some compensating action is taken. Conversely, if the level of overlapping between the neighboring cells is high, it is possible that most affected users could recover their communication by establishing a new connection with a neighboring cell without any compensating action. In this situation, the cell outage may not result in a coverage hole, since the neighboring cells absorb most of the traffic from the faulty cell. However, depending on the amount of absorbed traffic, neighboring cells could become overloaded. In addition, the outage may produce new neighbor relationships. If HO parameters are not correctly configured between these new neighbors, a mobility problem could be also produced by the outage. The aim of the compensation algorithm in these two last cases (i.e., cell overload and mobility problem) will not be to recover the lost traffic, but to mitigate the overload or mobility problem.

In this section, three different situations are considered:

- Cell outage that results in a coverage hole (*Coverage_ outage*): This situation occurs in scenarios where the overlapping areas between cells are very limited and/or the outage affects a large geographical area (e.g., when a whole site is down). Thus, the problematic area presents an important number of users that lose their connection.

- Cell outage that produces a congestion problem (*Load_ outage*): In this case, when the outage occurs, most users move to neighboring cells. This situation leads to a congestion problem due to the traffic absorbed by the neighboring cells.

- Cell outage that produces a mobility problem (*Mobility_ outage*): When a cell outage occurs and neighboring cells cover the problematic area, new neighbor relationships appear. If mobility parameters are not well configured between these new neighbors, different mobility problems can occur. One of these problems is the HO ping-pong [8].

A real network usually presents a very irregular layout. In such a scenario, the level of overlapping between neighboring cells or the load of the cells may be very different depending on the considered area. For this reason, when a cell or a group of cells (e.g., a whole site) is in outage, the neighboring cells of the cells in outage may present different types of degradation. When this occurs, the COC algorithm to be applied to each neighboring cell should be different. In this work, a scenario that combines more than one of the outage situations described above is also considered.

5.3.2 System model

The following paragraphs describe the control parameters and system measurements, which are later used as outputs and inputs of the compensation algorithm.

Control parameters

As described before, one of the most commonly used parameters in COC is the antenna tilt angle. Tunning this parameter is effective when the outage causes a coverage hole in the network. In order to consider the antenna tilt modifications as part of the COC methodology, the vertical antenna radiation pattern ($A_V(\theta)$) should be modeled [87]. The following expression represents the model considered in this work:

$$A_V(\theta) = -\min[12(\frac{\theta - \theta_{etilt}}{\theta_{3dB}})^2, SLA_v], \quad \text{where} -90^\circ \leq \theta \leq 90^\circ \tag{5.6}$$

where θ is the angle of inclination between the user and the eNB, θ_{3dB} is the vertical half-power beamwidth, θ_{etilt} is the electrical antenna downtilt (i.e., the angle of inclination of the transmitting antenna with respect to the horizontal plane) and SLA_v is the side lobe level in dB relative to the maximun gain of the main beam.

However, if the negative effects experienced by the neighboring cells are not related to a coverage degradation, antenna tilt modifications may not produce any improvement. For these other situations, HO parameter modifications are considered. One of the most widely used HO algorithms is that based on the A3 event defined by the 3GPP [88]. This event determines the condition that must be fulfilled to execute an HO, as

$$(RSRP_j) \geq (RSRP_i + HOM(i,j)) \, , \tag{5.7}$$

where $RSRP_i$ and $RSRP_j$ are the RSRP measured by the user from cells i and j, respectively, and $HOM(i,j)$ is the HOM defined between the cell i and neighbor j. The condition (5.7) must be fulfilled for a certain time period given by the TTT parameter.

A specific value of $HOM(i,j)$ and symmetric $HOM(j,i)$ allow to determine a certain HO hysteresis (HOH) that avoids unnecessary HOs. HOH can be calculated as follows:

$$HOH(i,j) = HOM(i,j) + HOM(j,i) = HOH(j,i) \, . \tag{5.8}$$

In addition, these two parameters (i.e., $HOM(i,j)$ and $HOM(j,i)$) can be used to apply a certain offset (HOoffset) that modifies the HO performance with load balancing purposes. Thus, HOM modifications can be made with different objectives: to modify the HOH or the HOoffset. On the one hand, $HOM(i,j)$ and the symmetric $HOM(j,i)$ can be jointly tuned to change HOoffset for load balancing purposes. In this case, the two margin parameters are modified with the same magnitude but opposite sign [89]. This kind of changes allows to modify the serving area of cells i and j, while maintaining HOH to avoid unnecessary HOs in the overlapped area between both cells. Alternatively, to adjust the HOH, the two margin parameters can be modified with the same magnitude and the same sign.

Fig. 5.5 illustrates different HO performance depending on the value of HOM parameters. Fig. 5.5(a) shows that a low value of HOM favors a user to perform an HO to a neighboring cell although it may produce an increase in unnecessary HOs (and, consequently, an increase in HOs ping-pong) due to signal fluctuations. Conversely, Fig. 5.5(b) shows that HOM may be configured to a higher value in order to avoid these unnecessary HOs. In this thesis, HOoffset modifications are used in case of a *Load_outage* situation and HOH changes are used in case of *Mobility_outage*.

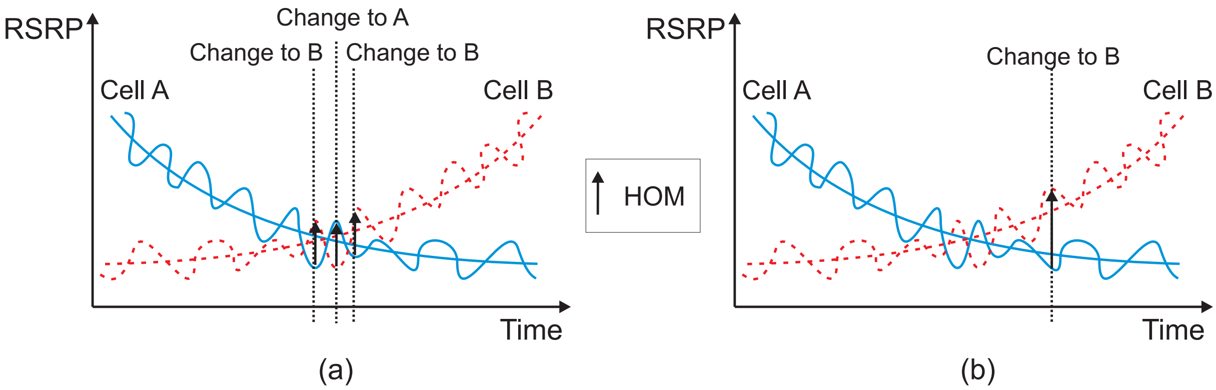

Figure 5.5: HO process for different values of HOM parameter: (a) small and (b) large.

System measurements

A set of performance indicators has been selected in order to analyze the proposed algorithms. Some of these KPIs constitute the inputs of the algorithms and allow to decide when a control parameter modification is needed and when the performed changes lead the network to the optimal performance. The selected KPIs are the following:

- Accessibility. This KPI indicates the capability of a cell to accept new connections. When a user requests a new connection to a certain cell, it may be blocked if the cell does not have enough available resources. The following expression indicates how to calculate this KPI:

$$Accessibility = 1 - \frac{N_{blocked}}{N_{attempts}}, \tag{5.9}$$

  where $N_{blocked}$ is the number of blocked connections and $N_{attempts}$ is the total number of connections attempts.

- Retainability. This indicator represents the capability of a cell to maintain active connections under different environment conditions. Its calculation depends on the number of dropped connections in a cell. When a user abnormally loses its connection due to connection quality or coverage problems, it is considered a dropped connection. The retainability can be expressed as the ratio:

$$Retainability = \frac{N_{succ}}{N_{drops} + N_{succ}} \,, \tag{5.10}$$

where N_{succ} is the number of successfully finished connections and N_{drops} is the number of dropped connections.

- HO ping-pong Ratio, HPR. This KPI shows the percentage of HO ping-pong occurred in a certain adjacency, calculated as the ratio between the number of HO ping-pong and the total number of HO executed. This KPI can be calculated as follows:

$$HPR = \frac{N_{HO\_PP}}{N_{executed}} \,, \tag{5.11}$$

where N_{HO_PP} is the number of HOs ping-pong occurred in a certain adjacency and $N_{executed}$ is the number of HO successfully executed in that adjacency. In particular, the N_{HO_PP} for a certain adjacency (i, j) is obtained from the total number of outgoing HOs from cell i and the number of outgoing HOs from cell j that return as incoming HO to cell i in a certain time period (ping-pong period).

- Percentage of blocked connections due to a lack of coverage (Block_Cov). This indicator measures the percentage of connections affected by a lack of coverage. A user is considered to be out of the coverage area of a cell if the best signal level received from that cell is below the minimum required signal value. If the user is out of the coverage area of the strongest cell in the scenario, the user is considered to be blocked due to a lack of coverage. The received signal strength is represented by the RSRP level. The Block_Cov for a certain cell is obtained by dividing the number of blocked connections due to a lack of coverage by the total number of connections measuring that cell with the highest RSRP value in the scenario. The following expression represents this KPI:

$$Block\_Cov = \frac{N_{blocked}}{N_{measured}} \,, \tag{5.12}$$

where $N_{blocked}$ is the number of blocked connections due to a lack of coverage in a cell and $N_{measured}$ is the total number of users that measured the cell as the strongest cell.

5.3.3 Cell Outage Compensation methodology

Fig. 5.6 shows the different phases of the proposed COC methodology. The COC methodology is triggered when a new cell outage problem is detected. Such a detection is carried out by the COD functionality presented in Chapter 4. When the COD algorithm detects a new cell outage problem, the cell outage analysis is carried out. This phase aims to analyze the kind of degradation produced in the neighboring cells by the cell outage. The details of this phase have been presented in the previous section. Depending on the kind of degradation detected, the most appropriate COC algorithm is selected for each neighboring cell.

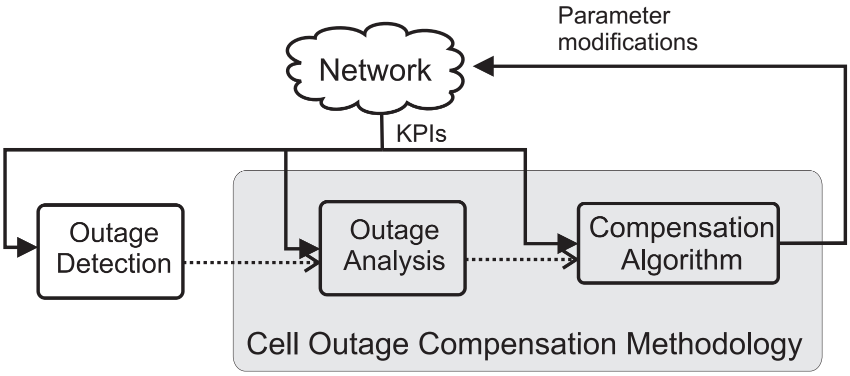

Figure 5.6: Cell Outage Compensation methodology.

The following sections are devoted to each phase of the methodology.

Cell outage analysis

In order to apply an adaptive COC method, it is essential to classify each cell outage situation when it is detected. The proposed method checks whether there is any degradation in the neighboring cells at the time of the cell outage and which KPIs are most affected. With that aim, the KPIs of the neighboring cells are correlated with a reference signal, as described in Section 5.2.2, which represents the cell availability along time of the cell in outage. Such a reference signal can be defined as the unit step function with the discontinuity corresponding to the first hour of the cell outage. In this work, the Pearson correlation coefficient (eq. 5.1) is used.

In addition to the correlation coefficient, the KPI value is compared to a pre-defined threshold. This threshold allows to determine if the detected degradation is severe enough to be compensated. A different threshold must be defined for each KPI. This threshold can be automatically calculated by the average of the specific KPI over a long time in a cell or over many cells in the network, assuming that most of the time there are no problems in the cells. An alternative method for the analysis, commonly used by operators, might be to directly compare the value of the KPI against the threshold, without considering the correlation. However, in a live network, 1) KPIs usually experience large fluctuations (i.e., spurious values) during normal behavior, and 2) the normal values can vary from cell to cell and also depending on network conditions. The correlation method avoids false positives and correctly detects degradation patterns in the neighboring cells' performance. Then, the defined threshold allows to determine whether this degradation is enough to be considered problematic.

Table 5.3 shows how the degradation produced by a cell outage in a certain neighboring cell is classified based on the affected KPIs in the three types described in Section 5.3.2: *Cov-*

erage_ outage, *Load_ outage* and *Mobility_ outage*. For clarity, in the following analysis of the three situations, it is considered that a cell outage affects all the neighboring cells in the same way.

When a *Coverage_ outage* has occurred, a coverage hole is produced in the outage area. In this situation, most users in the coverage area of the faulty cell lose their connection. The neighboring cells absorb only a small part of the affected users. The main degradation detected in the neighboring cells is an increase in Block_Cov. The only way to increase the number of users absorbed by the neighboring cells is extending their coverage area. The most appropriate solution for this situation is to perform tilt modifications in order to cover the outage area. Therefore, in the case of *Coverage_ outage*, the COC algorithm should be based on tilt modifications (COC_TILT) and the selected cells for the compensation action should be the neighboring cells affected by the coverage hole.

When the outage problem is a *Load_ outage*, the neighboring cells absorb most of the affected connections. Thus, the percentage of users out of coverage tends to be very low. However, a congestion problem may affect the neighboring cells when the amount of absorbed traffic is high enough. In this case, an increase of the coverage area would not significantly affect the percentage of absorbed traffic since most traffic has already been absorbed and would only worsen the congestion problem. In this situation, the aim of the compensation algorithm should be to mitigate the congestion problem. The most suitable method for this scenario is a COC algorithm based on HOoffset (COC_HOoffset). The aim of this algorithm is to reduce the serving area of the affected cells and increase the serving area of their own neighboring cells. Thus, the congestion may be reduced. The selected cells in this case should be the neighboring cells of the cell in outage (i.e., cells affected by congestion) and their own neighboring cells.

Finally, a cell outage may produce a mobility problem in its neighboring cells (i.e., *Mobility_ outage*). As in the case of *Load_ outage*, this kind of cell outage may not result in a coverage hole. Most of the affected traffic can be absorbed by the neighboring cells without any compensation action. Unlike *Load_ outage* situation, in this case, the neighboring cells do not experience a congestion problem. Since the neighboring cells cover the outage area, new neighbor relationships may appear. This situation may produce mobility problems if the HO parameters are not correctly configured between these new neighboring cells. One typical mobility problem that may appear is the HO ping-pong problem due to a wrong value of the HOH. HOH changes (COC_HOH) allow to reduce the number of HOs ping-pong. The selected cells for the compensation are the affected neighboring cells of the cell in outage.

As described above, in these two last cases (i.e., COC_HOoffset and COC_HOH), the adjusted control parameter is the HOM.

A cell outage may affect each neighboring cells in a different way. In this case, one cell outage may produce different outage situations depending on the considered neighboring cell. Likewise, a neighboring cell may suffer different types of degradation simultaneously due to the cell outage. The COC algorithm should adapt the compensation action of each neighboring cell

Table 5.3: Outage analysis

Type of outage	Degraded KPI	Parameter
Coverage_outage	Block_Cov	Tilt
Load_outage	Accessibility	HOoffset
Mobility_outage	HPR	HOH

to the detected outage situation. In the case that a cell experiences different types of degradation, the COC actions should be prioritized.

Cell Outage Compensation algorithms

This section presents the three compensation algorithms applied in this work to the cell outage problem. All the algorithms are based on fuzzy logic. This technique is especially suitable to be applied to cellular networks since it allows to take decisions from imprecise information. In addition, the description of control actions in linguistic terms in fuzzy logic systems favors that the operator's experience can be easily applied to the problem. In particular, three Fuzzy Logic Controllers (FLC) have been defined, one for each compensation algorithm. All of them are designed according to the Takagi-Sugeno approach [90].

Fig. 6.2 presents the main blocks in an FLC. The first stage, *fuzzifier*, is in charge of transforming the numerical input values into fuzzy inputs. This mapping is based on membership functions, . Several membership functions are defined for each input of the FLC, determining the degree of membership of any numerical input to different fuzzy sets. A linguistic term represents each defined fuzzy set. In this work, the terms High, Medium and Low are used. The values of the degree of membership is a real value between 0 and 1. The next stage is the inference engine which is based on a set of IF-THEN rules. The definition of these rules is based on the knowledge and experience of human experts, and with the ultimate goal of performing the appropriate compensation. Rules determine different situations that can occur with the corresponding action that the FLC should execute. Based on these rules, the inference engine calculates the output fuzzy sets. Specifically, depending on the input fuzzy sets, different rules may be activated with different strength (α). The activation strength of a rule k, α_k, is calculated by the product operator:

$$\alpha_k = \mu(input_1) \cdot \mu(input_2) \ . \tag{5.13}$$

Each rule produces a certain output (e.g., a constant value with an associated linguistic term, o). As result, a fuzzy output, $\alpha \cdot o$, is generated for each rule. Finally, the *defuzzifier* calculates the output crisp value from the results of the previous stage. In particular, depending on the rules' outputs and the activated rules with the corresponding activation strength , the final crisp output is obtained as a weighted average as follows:

$$output = \frac{\sum_{i=1}^{N} \alpha_i \cdot o_i}{\sum_{i=1}^{N} \alpha_i} , \tag{5.14}$$

where N is the number of rules, o_i is the output of rule i and α_i is the activation strength of the rule i.

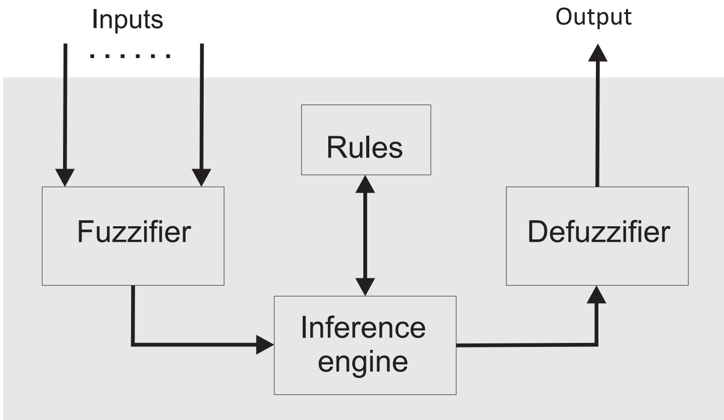

Figure 5.7: Block diagram of a Fuzzy Logic Controller.

The three algorithms presented hereafter differ in the considered inputs and outputs, the fuzzy sets and the rules. The configuration details for each method are explained in the following paragraphs.

COC_TILT algorithm

In this case, the aim of the algorithm is to increase the coverage area of the neighboring cells in order to cover a coverage hole. The FLC is executed separately for each selected neighboring cell (i.e., there is a FLC for each neighbor). The considered inputs are the Block_Cov and the Accessibility. The output of the FLC is the increment that must be applied to the antenna tilt of each neighboring cell. Fig. 5.8 shows the membership functions defined for each input. Three fuzzy sets have been defined for Block_Cov (i.e., Low, Medium and High) and two fuzzy sets have been defined for Accessibility (i.e., Low and High). The values selected for the different thresholds in the membership functions are similar to typical limits accepted by network operators. Table 5.4 presents the set of control rules, where L is Low, M is Medium and H is High. As for the fuzzy outputs, Negative means a decrease of the antenna tilt of 1° (i.e., uptilt), Null means no change in antenna tilt and Positive means an increase of the antenna tilt of 1° (i.e., downtilt). For instance, rule 1 can be read as: 'IF (Block_Cov is Low) AND (Accessibility is Low) THEN ($\Delta Tilt$ is Positive)'. Each rule has been defined with a certain objective. Rules 4 and 6 are activated when the neighboring cell is suffering coverage problems but not congestion. Rule 1 is activated when the absorbed traffic begins to produce a congestion problem in the neighboring cell. Rules 3 and 5 avoid changes so that Accessibility is not deteriorated. Finally, rule 2 is in charge of maintaining the compensation situation once it is achieved. The obtained output crisp value is a real value that is rounded to -1, 0 or 1 (standing for Negative, Null or Positive, respectively). Finally, the resulting tilt value obtained by adding the increment to the previous tilt value is limited to $[0° - 12°]$ to avoid excessive changes.

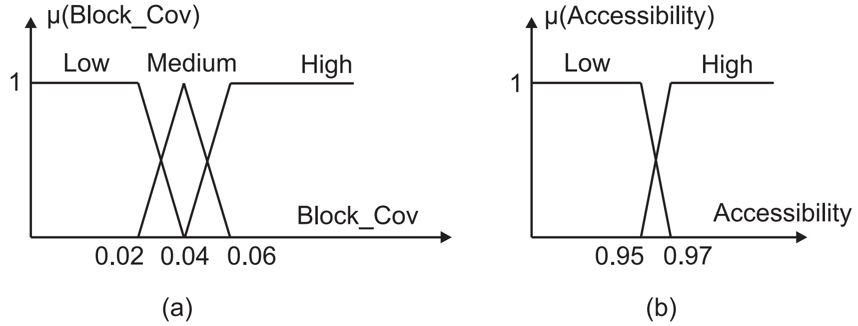

Figure 5.8: Input membership functions for (a) Block_Cov and (b) Accessibility.

Table 5.4: Control Rules for COC_TILT algorithm

No	*Block_Cov*	*Accessibility*	$\Delta Tilt$
1	L	L	Positive
2	L	H	Null
3	M	L	Null
4	M	H	Negative
5	H	L	Null
6	H	H	Negative

COC_HOoffset algorithm

This algorithm aims to change the service area of cells without modifying the hysteresis. This means that all changes to $HOM(i, j)$ should be applied with equal magnitude and opposite sign to $HOM(j, i)$, as explained in Section 5.3.2. The aim of this algorithm is to balance the load between the neighboring cells of the cell in outage (which have absorbed the traffic from the outage area) and their own neighboring cells. These last cells should not be neighbors of the cell in outage. Hereafter, each neighboring cell of the cell in outage is referred to as 'serving cell' and its neighboring cells are referred to as 'adjacent cells'. The FLC is executed for each pair of serving and adjacent cell (i.e., there is a FLC per adjacency). The considered inputs are the Accessibility for the serving cell, s, the Accessibility for the adjacent cell, a, the current value of the HOM parameter, $HOM(s, a)$, and the Retainability for the adjacent cell. Fig. 5.9 shows the membership functions defined in this case. Two fuzzy sets have been defined for both KPIs: Low and High. The values selected for the different thresholds related to Accessibility and Retainability are again typical limits accepted by network operators. As for the $HOM(s, a)$, the parameter is considered High if the value is above 1 and Low if the value is below -1. A Low $HOM(s, a)$ value facilitates the HO from the serving cell to the adjacent cell, thus offloading the serving cell. Table 5.5 presents the set of control rules, where L is Low and H is High. Rule 5 is activated when a load balance is needed, regardless of the current HOM value. In the case that the adjacent cell experiences problems related to Accessibility (rules 1 and 2) or Retainability (rules 4 and 5), a Positive change is applied only if the situation is produced by an excessive modification of HOM. Finally, rule 6 maintains the compensation situation once it is achieved. The output of the FLC, ΔHOM, represents the modification to be applied to $HOM(s,a)$. The same modification with opposite sign must be applied to $HOM(a,s)$. The resulting output increment values are rounded to -1, 0 or 1 dB (Negative, Null, Positive, respectively) and the HOM values are limited to [-12 - 12] dB.

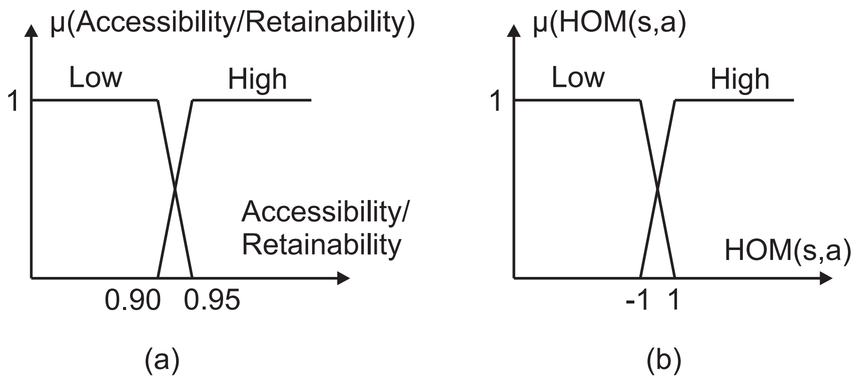

Figure 5.9: Input membership functions for (a) Accessibility and Retainability and (b) $HOM(s,a)$.

Table 5.5: Control Rules for COC_HOM algorithm

No	Acc (s)	Acc (a)	HOM (s,a)	Ret (a)	ΔHOM (s,a)
1	-	L	H	-	Null
2	-	L	L	-	Positive
3	-	H	H	L	Null
4	-	H	H	L	Positive
5	L	H	-	H	Negative
6	H	H	-	H	Null

COC_HOH algorithm

The aim of this algorithm is to modify the HOH in order to improve the HO performance between the neighboring cells when a cell outage occurs. To modify the hysteresis level, the modifications should be applied to $HOM(i,j)$ and $HOM(j,i)$ with the same sign and magnitude. The FLC is executed for each degraded adjacency between the neighboring cells of the cell in outage. The considered inputs are the $HPR(i,j)$ per adjacency and the Retainability for cell i and for cell j. Fig. 5.10 presents the membership functions. As in the previous case, two fuzzy sets have been defined: Low and High. The values for the different thresholds have been selected according to the performance of the considered scenario in a normal situation. Table 5.6 shows the set of control rules, where L is Low and H is High. Rule 8 produces an increase of HOM when HPR is high. Rules 4, 6 and 7 are activated when the compensation action must be reverted if any cell begins to experience a Retainability degradation and the HPR is low. Rules 1, 2 and 3 avoid changes if any cell suffers a Retainability degradation although the HPR is high. Finally, rule 5 maintains the compensation situation once it is achieved. The output, ΔHOM, represents the increment that must be applied to $HOM(i,j)$ and $HOM(j,i)$. The resulting output crisp value is rounded to -0.5, 0 or 0.5 dB (Negative, Null, Positive, respectively) and the final HOM values are limited to [0 - 12] dB.

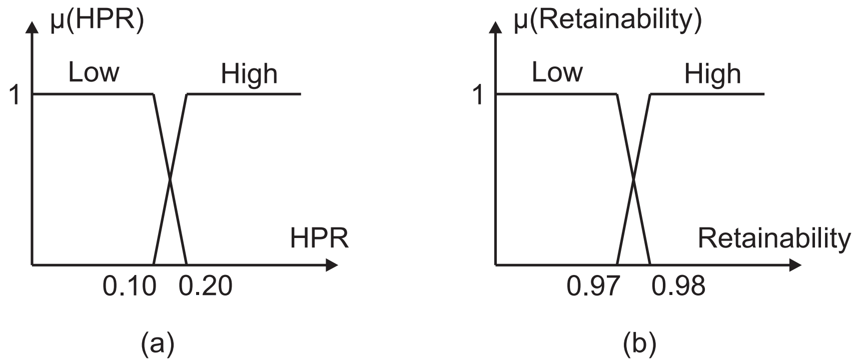

Figure 5.10: Input membership functions for (a) HPR and (b) Retainability.

Table 5.6: Control Rules for COC_HOH algorithm

No	HPR (i,j)	Ret (i)	Ret (j)	ΔHOM (i,j)
1	H	L	L	Null
2	H	H	L	Null
3	H	L	H	Null
4	L	H	L	Negative
5	L	H	H	Null
6	L	L	H	Negative
7	L	L	L	Negative
8	H	H	H	Positive

5.3.4 Performance analysis

For clarity, the simulation setup is first described. Then, a preliminary sensitivity analysis is presented. Finally, performance results are discussed.

Simulation setup

The dynamic LTE system level simulator presented in Chapter 3 has been used in this work to asses the proposed COC methodology. The realistic scenario is considered in this section. Table 5.7 presents the main configuration parameters of the simulations. In general, simulations consist of a set of simulation loops. The considered KPIs are estimated at the end of each loop. Based on the KPIs values, a change of a control parameter is introduced, which is applied in the next loop. Each loop comprises many simulation steps, each of 100ms of network time. During each step, the main RRM functions (i.e., HO, cell selection, admission control and packet scheduler) are executed. The duration of each loop is set to 30000 steps (i.e., 50 minutes) in order to ensure reliable statistics. It should be pointed out that these times can be reduced when the algorithm is applied to a real network. In this case, each execution of the COC algorithm can be performed once the KPIs are updated. The periodicity of updating the KPIs in a real network can be less than an hour (e.g., 15 minutes), so that the total time to achieve a compensation situation can be reduced.

Table 5.7: Simulation parameters

Parameter	Configuration
Cellular layout	Real scenario, 75 cells (25 eNBs)
Carrier frequency	2.0 GHz
System bandwidth	1.4 MHz
Propagation model	Okumura-Hata Log-normal slow fading, $\sigma_{sf} = 8$ dB correlation distance=50 m
Channel model	Multipath fading, ETU model
Mobility model	Random direction, 3 km/h
Service model	Full Buffer, poisson traffic arrival
Base station model	Tri-sectorized antenna, SISO, Azimuth beamwidth=70° Elevation beamwidth=10° $P_{TX_{max}}$ =43 dBm
Scheduler	Time domain: Round-Robin Freq. domain: Best Channel
Handover	Triggering event = A3 Measurement type = RSRP Initial HOM = 2 dB TTT = 100 ms ping-pong period = 5 s
Radio Link Failure	$SINR < -6.9\ dB$ for 500 ms
Time resolution	100 TTI (100 ms)

Fig. 5.11 shows the simulated scenario in a normal situation. Specifically, the figure presents the RSRP received from the strongest cell in each point of the scenario. The different cells are numerated to facilitate the understanding of the tests.

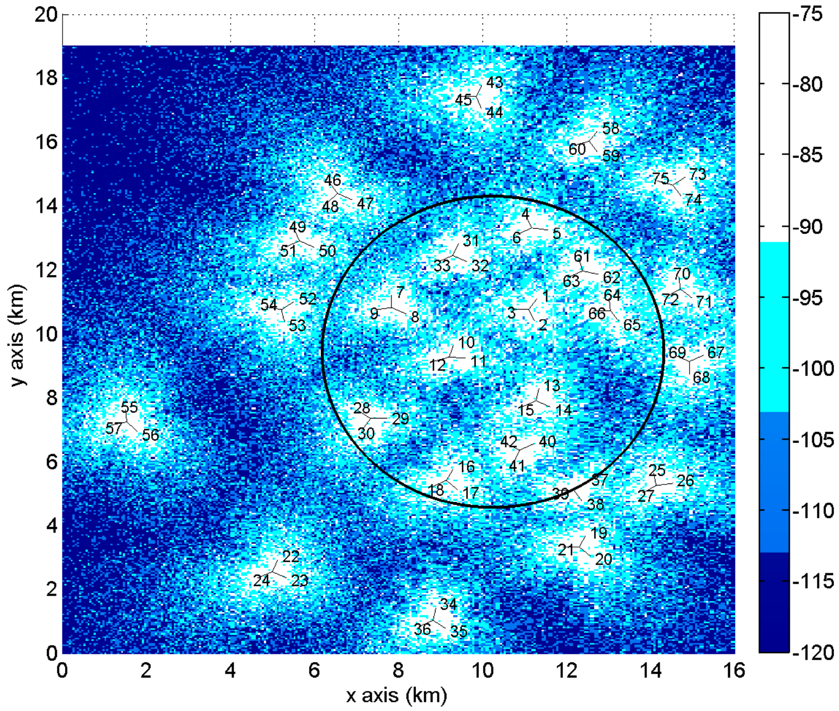

Figure 5.11: RSRP values in the simulation scenario (dBm).

Sensitivity analysis

State-of-the-art COC algorithms, which are based on power or tilt modifications, are devised to specifically solve coverage problems. However, when an outage problem occurs in a network different effects may appear, not limited to coverage holes. A sensitivity analysis is carried out to illustrate that a certain COC algorithm may not be appropriate for a specific outage case. The selected outage situations are those explained in Section 5.3.2. For clarity, it is assumed in this section that a certain cell outage causes the same degradation in all of its neithboring cells. The different effects produced by a cell outage depend on the network conditions in the outage area. Thus, cells 10, 11 and 12 (Fig. 5.11) have been selected to suffer a cell outage that produces a coverage hole, since this site has the largest serving area in the considered network. Conversely, when cells 1, 2 and 3 (Fig. 5.11) are in outage, the outage area is automatically covered by the neighboring cells so that the outage does not cause a coverage hole. In this case, two different situations may occur depending on network conditions during normal performance. On the one hand, it is possible that the neighboring cells that have absorbed the traffic from the outage area suffer a congestion problem. This situation may occur if the amount of traffic in the normal situation is large enough and the new absorbed traffic exceeds the capacity limit of the cells. In addition, the quality of the radio channel of the new connections served by neighboring cells will be worse than in the normal situation. As a consequence, link adaptation in LTE leads to a higher consumption of radio resources, increasing the congestion probability. It is worth noting that, although in the normal situation the amount of traffic may be large, the network performance is still good, as there is no congestion problem. On the other hand, a mobility problem may happen. When a cell outage occurs, new neighborly relationships appear. The performance of the HO process may be degraded if the HO parameters are not correctly configured for these new neighbors. In all cases, the considered set of neighboring cells are the neighbors in the first tier.

The sensitivity analysis carried out consists of applying different control parameters modifications to these three outage situations. The considered control parameters are the antenna tilt and the HOM (used for HOoffset and HOH modifications). The default configuration of the network parameters are based on the actual values used in the live network considered in this work. Thus, the default value of the HOM is 2 dB (HOH equal to 4 dB) and the antenna tilt is configured to values between 2° and 7°. Such a default configuration leads to an average cell load of 80% in terms of PRB utilization ratio. As described before, the degradation produced by the cell outage depends on network conditions. To facilitate the occurrence of the different kind of degradations in the simulated scenario, some network parameter setting have been modified. To create a *Mobility_ outage* case, the initial value of the HOM is configured equal to zero (HOH equal to zero) and the antenna tilt is equal to 7° for the selected cells (i.e., neighboring cells of the cells in outage). To create a *Coverage_ outage* case, the default value of the antenna tilt for the neighboring cells is configured to 9° to facilitate the occurrence of the coverage hole. Finally, the initial load of the neighboring cells in the case of *Load_ outage* is set to 95% to favor congestion problems. Note that these parameter changes do not cause any performance problem in the network during normal behavior, when no cell outages occur.

During the sensitivity tests, the antenna tilt is reduced by 1° per simulation loop (i.e., uptilting) in the *Coverage_ outage* case, the HOM is modified by 1 dB per simulation loop in the *Load_ outage* case and 0.5 dB per simulation loop in the *Mobility_ outage* case.

Fig. 5.12 - 5.14 show the results of the sensitivity analysis. Each figure corresponds to a different outage situation, showing the value of the most significant KPIs for that case. The average value across neighboring cells is presented. In all cases, the simulation consists of three phases. First, a normal behavior of the network is simulated. KPI values during this phase (loops 1-2) are considered as a baseline. Second, a cell outage is simulated. In this phase (loops 3-4), no compensation actions are applied. Thus, the degradation produced by the outage can be analyzed. Finally, in the third phase (loops 5 and later), the sensitivity analysis is carried out. During this phase, incremental changes are applied to the corresponding parameter (i.e., antenna tilt or HOM).

Fig. 5.12 shows the results in the case of *Coverage_ outage*. In this situation, the considered KPIs are Block_Cov and Accessibility. When a cell outage occurs (loops 3-4), the percentage of blocked connections due to bad coverage increases significantly indicating that a coverage hole is created. In the rest of loops, compensation is carried out by progressively modifying the corresponding parameter. Specifically, the final values reached for each parameter (loop 11) are: 1° for the antenna tilt, 5.5 dB for $HOM(i,j)$ and $HOM(j,i)$ in the HOH case and 9 dB for $HOM(i,j)$ and -5 dB for $HOM(j,i)$ in the HOoffset case. Results show that only the antenna tilt modification achieves a compensation situation similar to the normal behavior. After uptilting, the neighboring cells absorb almost all the traffic from the outage area reducing the percentage of users without coverage. It can be seen that the tilt modifications causes a decrease in Accessibility. However, this decrease in Accessibility (0.02 in absolute terms) is smaller than the benefit in Block_Cov (0.04 in absolute terms).

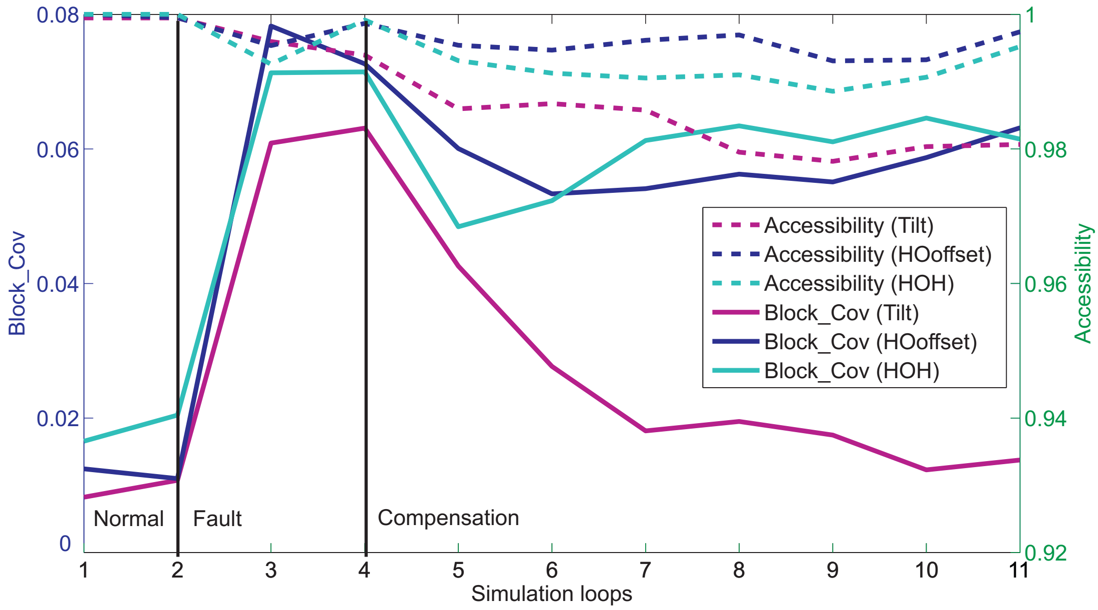

Figure 5.12: Sensitivity analysis for *Coverage_ outage* case.

In the *Load_ outage* case, Accesibility is the most important KPI. Fig. 5.13 presents the Accessibility and the Retainability of two groups of cells. On the one hand, cells of Group A are the neighboring cells in the first tier of the cells in outage. These cells are those with the congestion problem after the outage. On the other hand, cells of Group B are the neighboring cells of the congested cells. For the compensation algorithm described in Section 5.3.3, cells of Group A are considered as serving cells and cells of Group B are considered as adjacent cells. Fig. 5.13 shows the Accessibility for cells in Group A and the Retainability for cells in Group B, as these are the most significant KPI for each group of cells. The final values achieved for each parameter (loop 14) are: 0° for the antenna tilt, 6.5 dB for $HOM(i,j)$ and $HOM(j,i)$ in the HOH case and 11 dB for $HOM(i,j)$ and -7 dB for $HOM(j,i)$ in the HOoffset case. In this outage situation, the neighboring cells of the cell in outage (i.e., Group A) automatically cover the outage area. This fact causes a congestion problem in these neighboring cells that absorb traffic from the outage area. The important decrease presented in Accessibility indicates the congestion problem. In this situation, the compensation method that achieves a compensation situation similar to the normal behavior is the one based on changing HOoffset. The HOoffset modifications achieve load balancing between the two groups of cells. The main negative effect produced by this method is a degradation in the Retainability of cells in Group B, which can be of up to 0.1 in absolute terms. Not shown is the fact that these changes cause a negligible degradation of the Accessibility of cells in Group B.

Finally, Fig. 5.14 shows the results obtained for the *Mobility_ outage* case. The final values

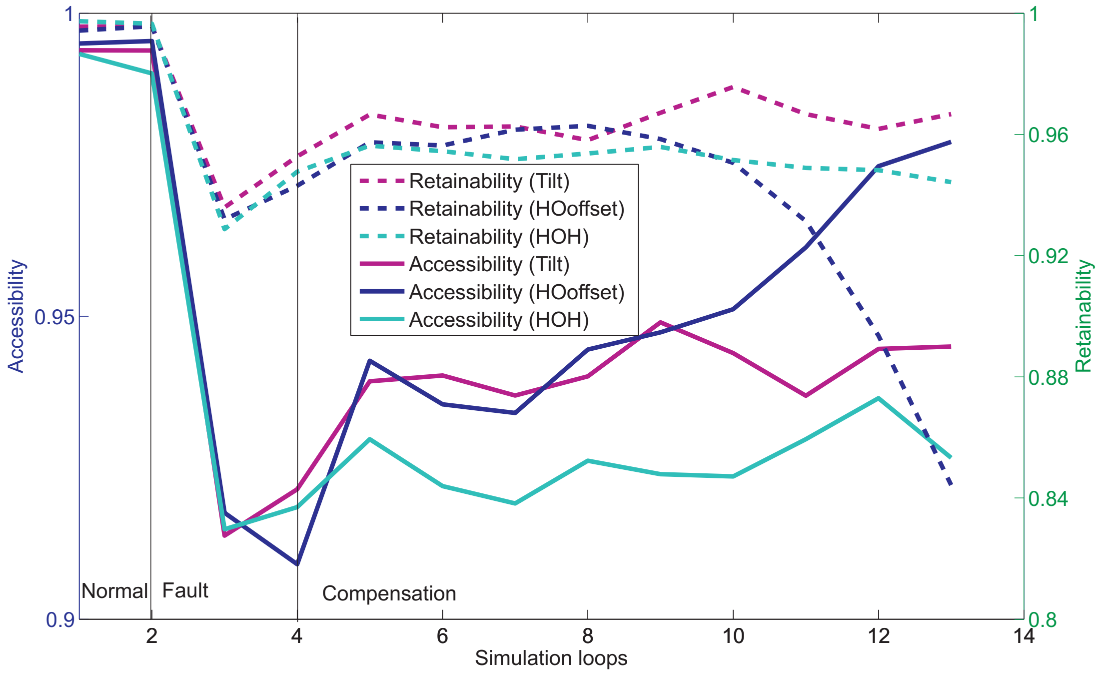

Figure 5.13: Sensitivity analysis for *Load_ outage* case.

achieved for each parameter (loop 14) are: 0° for the antenna tilt, 4.5 dB for $HOM(i,j)$ and $HOM(j,i)$ in the HOH case and 9 dB for $HOM(i,j)$ and -5 dB for $HOM(j,i)$ in the HOoffset case. When the outage occurs, an important increase of the HPR between some new neighbors is observed. This increase is caused when there are misconfigured HO parameters. This problem is negligible during the normal behavior of the network because, before the outage, there are no HOs between these cells. In a *Mobility_ outage* situation, only an increase of the HOH manages to reduce the HPR. In this case, it is important to consider that a high value of the HOH may lead to a decrease in connection quality and, consequently, a decrease in Retainability. However, Fig. 5.14 shows that the improvement of the HPR is achieved before Retainability is degraded.

Algorithm performance

In the previous sensitivity analysis it has shown that different outage situations must be compensated by modifying different parameters. Specifically, for the outage situations considered in this work, the *Coverage_ outage* should be compensated by antenna tilt modifications, the *Load_ outage* should be compensated by HOoffset modifications and, finally, the *Mobility_ outage* can be successfully compensated by modifying the HOH. This section presents the results obtained when each proposed FLC-based COC algorithm is applied to the corresponding outage situation. In this case, it is also assumed that each outage situation causes the same degradation in the neighbors of the cells in outage. As in the sensitivity analysis, the simulation consists of three phases; normal behavior (loops 1-2), fault (loops 3-4) and compensation (loops 5 and thereafter). During the last phase, the COC algorithm initiates the compensation process and achieves a stable compensation situation.

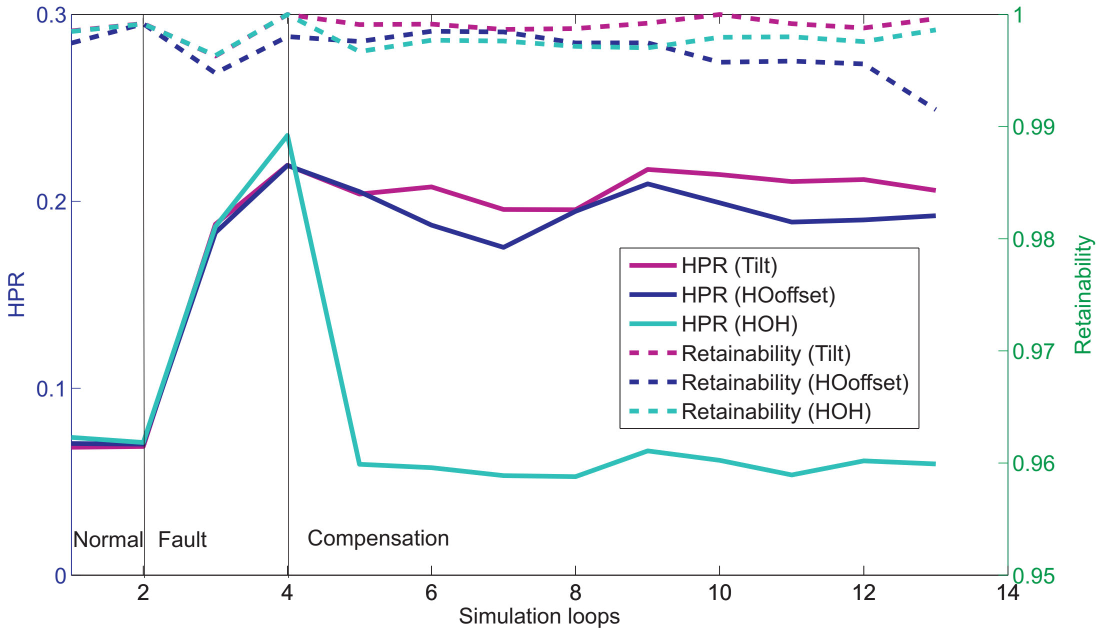

Figure 5.14: Sensitivity analysis for *Mobility_ outage* case.

Fig. 5.15 shows the results obtained in the application of the COC_TILT algorithm to a *Coverage_ outage* problem. The figure presents the average value for the neighboring cells for Block_Cov and Accessibility KPIs. The cell outage failure affects cells 10, 11 and 12, belonging to the same site (Fig. 5.11) and the selected neighboring cells are neighbors in the first tier (i.e., cells 8, 15, 28 and 29). During compensation, the minimum achieved value for the antenna tilt is 6°. In the normal situation, this site covers a large geographical area. When the cell outage occurs, an important percentage of users suffer lack of coverage. When compensation is activated, this percentage decreases significantly. This decrease is achieved by uptilting the degraded neighboring cells to absorb the users in the outage area. While neighboring cells are accepting new users, its Accessibility is slightly degraded. The proposed algorithm achieves a balanced situation with a significant decrease of the Block_Cov and a slight degradation of the Accessibility.

Fig. 5.16 presents the results for the *Load_ outage* problem. The cells in outage are cells 1, 2 and 3. In this case, the outage failure causes a congestion problem in cells 11, 13, 63 and 66 (i.e., Neighbors Group A). The set of cells selected to carry out the compensation are 12, 14, 15, 61, 62, 64 and 65 (i.e., Neighbors Group B). The applied algorithm (i.e., the COC_HOoffset algorithm) performs parameter changes similar to a load balancing algorithm. Thus, the main KPIs that should be considered in this test are Accessibility and Retainability of both groups of cells (i.e., Accessibility of cell in Group A and Retainability of cells in Group B), Fig. 5.16. It can be seen that the algorithm improves the Accessibility of the neighboring cells of Group A (i.e., cells with congestion problems) without degrading the Retainability of the cells used for the compensation (i.e., Neighbors Group B). The maximum modification applied to HOM is 8 dB (i.e., 10 dB for $HOM(i, j)$ and -6 dB for $HOM(j, i)$).

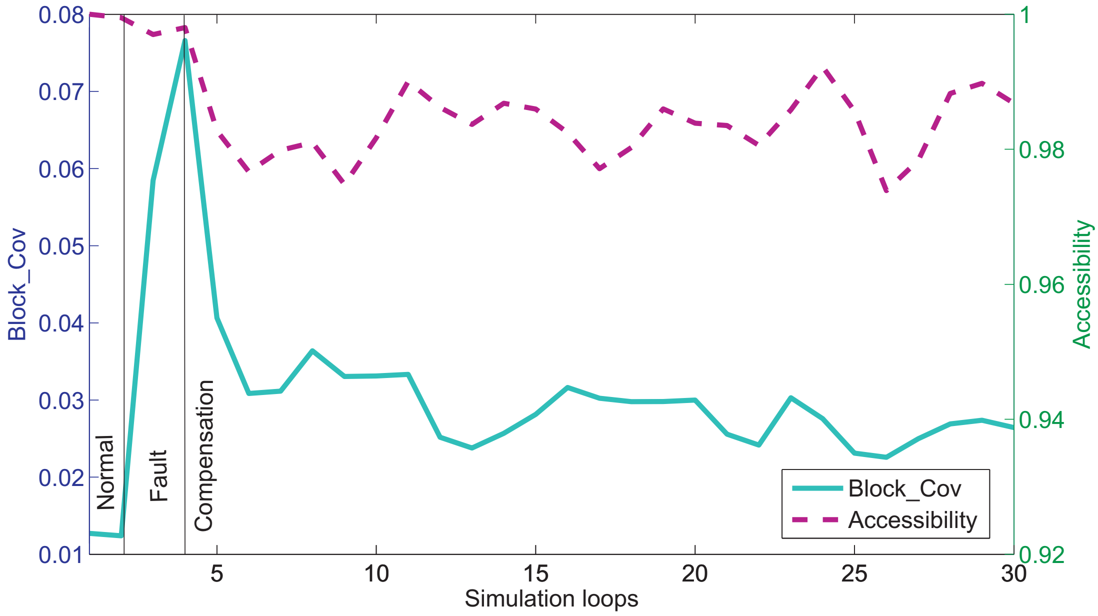

Figure 5.15: Results for the COC_TILT algorithm in the *Coverage_ outage* case.

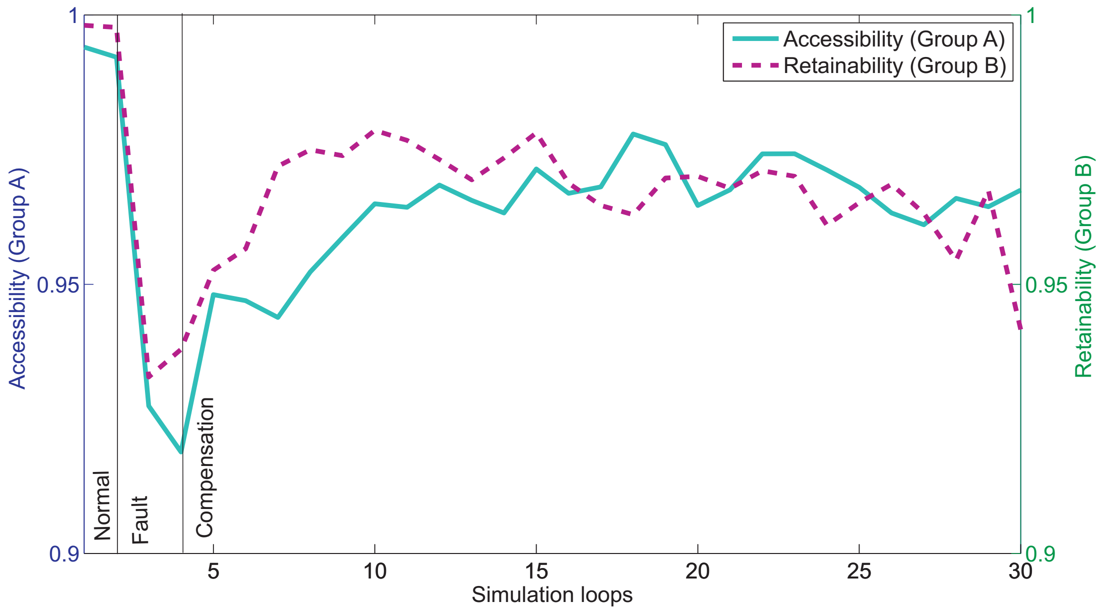

Figure 5.16: Results for the COC_HOoffset algorithm in the *Load_ outage* case.

Finally, the COC_HOH algorithm has been tested. This algorithm is applied to a *Mobility_ outage* failure. As described in the previous section, for this test, the HOH for the neighboring cells is configured to zero, so that the initial hysteresis level is too low. Fig. 5.17 presents the average value of HPR and Retainability for the degraded neighboring cells (i.e., cells 10, 32, 63 and 66 in the first tier). By increasing the HOH value between the affected cells, it is possible to reduce the HPR. A value closer to that in the normal situation is achieved in the first iteration of the algorithm avoiding a degradation in Retainability. The maximum value for the HOH at the end of the tuning process is 2 dB.

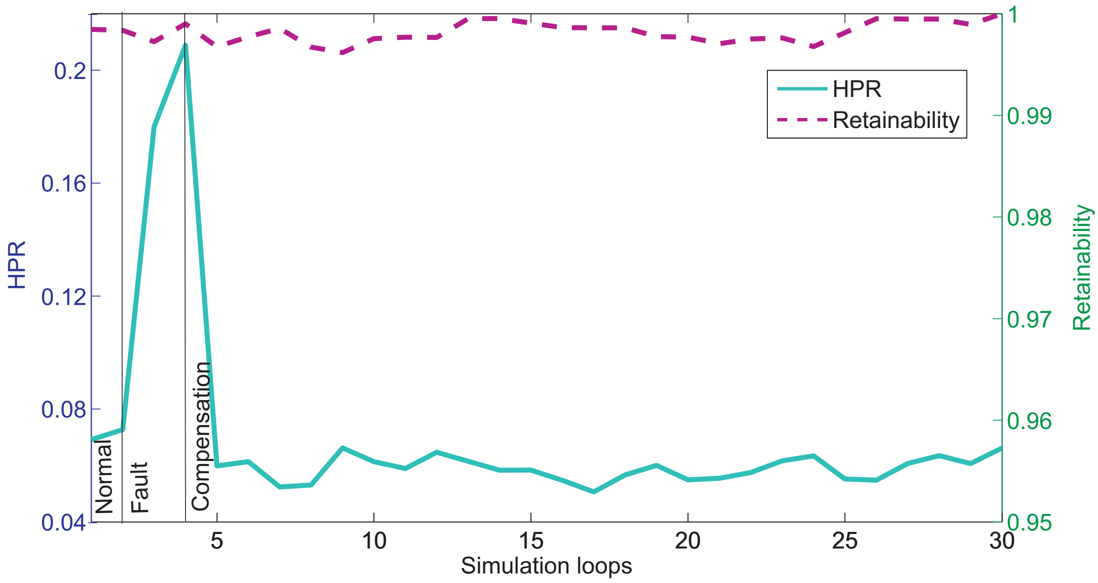

Figure 5.17: Results for the COC_HOH algorithm in the *Mobility_outage* case.

For clarity, in the previous tests, it has be assumed that a cell outage affects in the same way all the neighboring cells. Thus, different strategies have been analyzed. In the last experiment, a more realistic situation is presented, where different neighboring cells show different effects from the outage. Specifically, a cell outage in cells 10, 11 and 12 is studied. This cell outage may cause different degradation in each neighboring cell. Once the specific degradation is detected for each neighboring cell, the corresponding COC algorithm is applied in the specific neighbor.

The configuration is similar to that used in the *Coverage_outage* test, but with a new hot-spot near cells 13 and 15. These conditions allow to simulate a cell outage causing a coverage hole in the outage area and a congestion problem in cells 13 and 15.

Once the cell outage occurs, the analysis of the degradation is carried out. For each neighboring cell, the correlation of the reference signal and each considered KPI (i.e., Block_Cov, Accessibility and HPR) is calculated. Table 5.8 shows the obtained results. According to these results and considering degradation when the correlation coefficient is higher than 0.9, it can be concluded that cells 8, 13, 15 and 29 may be affected by the coverage hole; cells 13 and 15 may be suffering a congestion problem; and cells 3, 8 and 13 may experience a mobility problem. These results must be completed with the comparison to the pre-defined thresholds. To classify a certain neighboring cell as degraded cell, the value of Block_Cov has to be higher than 0.06, the value of Accessibility has to be lower than 0.96 and the value of HPR has to be higher than 0.2. Thus, after comparing to the thresholds, the analysis determines that cells 8 and 29 are affected by the coverage hole, while cells 13 and 15 experience a congestion problem. The rest of neighbors in the first tier are not significantly affected. Fig. 5.18 and Fig. 5.19 show the obtained results. Specifically, Fig. 5.18 shows the average value of the KPIs Block_Cov and Accessibility for cells 8 and 29. For these cells, the COC_TILT algorithm is applied to reduce Block_Cov by uptilting these cells. This is achieved at the expense of reduction of Accessibility. To avoid this negative effect, the COC_HOoffset could be applied, once Accessibility degradation appears.

Fig. 5.18 does not consider this alternative.

Table 5.8: Correlation results for the analysis phase

	Block_Cov	Accessibility	HPR
Cell 2	0.08	0	0.47
Cell 3	0.69	0	-0.94
Cell 8	0.99	-0.61	-0.92
Cell 13	0.98	-0.97	-0.91
Cell 15	0.95	-0.98	-0.75
Cell 28	0.61	0	-0.67
Cell 29	0.95	-0.61	-0.54

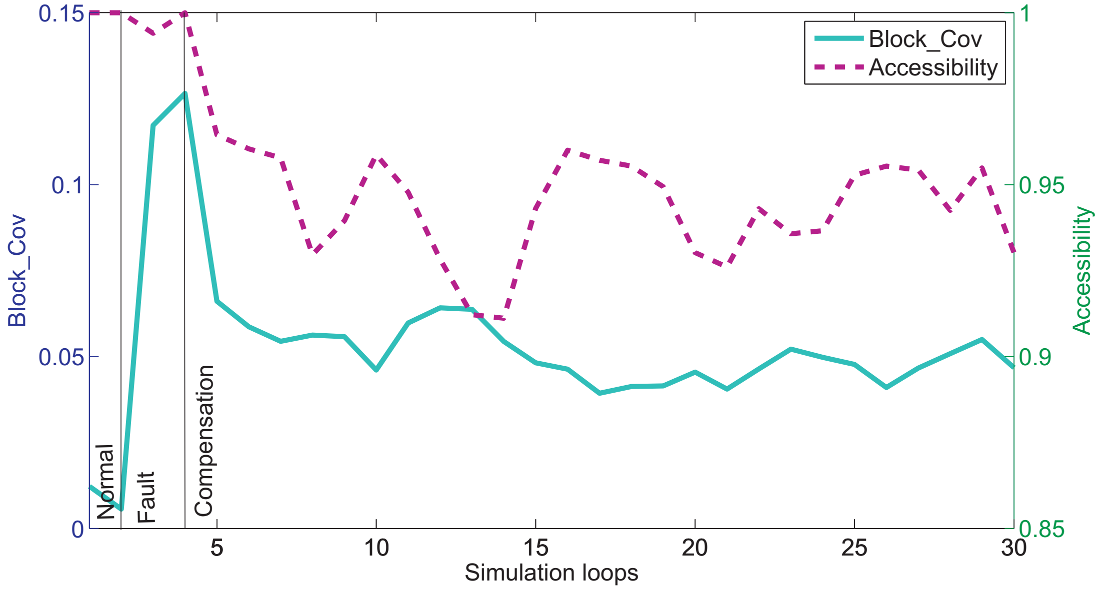

Figure 5.18: Results for coverage hole problem.

Simultaneously, cells 13 and 15 are affected by a congestion problem (Fig. 5.19). Following the same nomenclature that in previous tests, these two cells are considered Neighbors Group A and the set of cells used to reduce the congestion are Neighbors Group B (i.e., cells 2, 3, 14, 29, 40, 42, 69, 72). In this case, the COC_HOoffset algorithm is applied to compensate the congestion problem. Along simulation loops, Accessibility of the affected cells is increased but a slight degradation of Retainability of the cells from Group B is produced. However, the achieved Retainability values remain in an acceptable margin.

5.4 Conclusions

This chapter has focused on the COC function. A novel COC methodology has been presented. The method adapts the compensation action on a per-neighbor basis according to the degradation produced by the cell outage in each neighboring cell. The adaptation consists of automatically

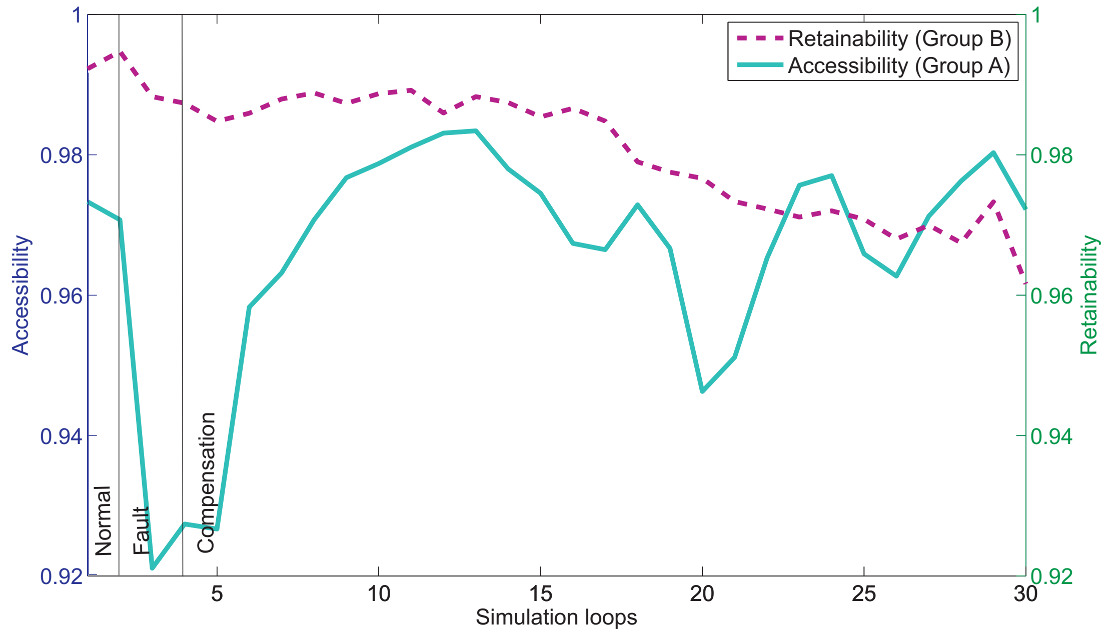

Figure 5.19: Results for congestion problem.

selecting the compensating cells, the configuration parameters to be modified and the magnitude of the compensating action.

As part of this new COC methodology, a study of the degradation produced by cell outages in the neighboring cells in a real network has been presented. Specifically, three new analysis methods have been proposed. A first offline method aims to analyze the degradation produced by the cell outage in the neighboring cells by correlating KPIs using historical records of cell outages. The two other methods are online approaches, which are executed immediately after the outage detection. These online methods are distinguished by the way that degradations in KPIs are determined. One of them is based on correlations and the other is based on delta detection. Both methods allow to determine the type of cell outage so as to effectively adapt the compensation algorithm. In addition, a method for estimating the lost traffic caused by a cell outage has been presented. Results have shown that cell outages may result in different issues that are reflected by different types of degradations in the neighboring cells. Such a set of different situations should be compensated in a different way.

Then, an adaptive COC methodology comprising several COC algorithms has been proposed. Once the previous analysis method has determined the set of affected neighboring cells and the type of degradation caused by the cell outage, a different COC algorithm can be applied to each neighboring cell. In particular, three different cell outage situations are considered in this work: one for compensating coverage degradation, another one for alleviating load congestion degradation and one for solving mobility problems. The different COC algorithms solve the effects of the outage by modifying antenna tilt, HOM or HOH. A sensitivity analysis has been carried out to show how different types of cell outage situations should be compensated by modifying different control parameters. Results show that, for each cell outage problem, only one COC strategy achieves a successful compensation. Based on the previous observation, three COC algorithms implemented by FLC have been applied to different cell outage failures. In all cases, the COC algorithm manages to compensate the degradation produced by the cell outage without affecting other cells in the scenario. Finally, a more realistic scenario has been tested where the cell outage causes different types of degradation in the neighboring cells simultaneously. Results show that the proposed COC methodology successfully compensates the fault situation.

Chapter 6

Cell Degradation Compensation

A novel CDC algorithm based on HOM modifications is presented in this chapter. Unlike the previous chapter, the fault considered here is weak coverage due to a power fault. In this faulty situation, the problematic cell is active during compensation, but its power is abnormally low. Section 6.1 presents the related work. Sections 6.2 and 6.3 outline the problem formulation and the system model. The proposed algorithm is presented in Section 6.4. Performance results are analyzed in Section 6.5.2. Finally, Section 6.6 summarizes the conclusions.

6.1 Related work

This chapter presents a compensation algorithm that tries to mitigate the degradation caused by a fault different from a cell outage problem. Nonetheless, the related work includes all the studies about the compensation function. Thus, state-of-the-art COC algorithms presented in Section 5.1 can be considered as the related work in this chapter too.

From the analysis presented in Section 5.1, it can be concluded that most compensation and coverage optimization algorithms have been applied to the same network failure, i.e., a cell outage. However, there are many other network failures that may cause an important degradation in network performance [46]. In this case, the faulty cell may carry traffic and it can therefore be considered for compensation. When this occurs, new parameters, such as HOM, can be considered to perform the compensation. This parameter has been extensively used for network performance optimization. In that context, the aim of adjusting HOMs has typically been the optimization of the HO process [91] or load balancing in case of congestion [89] in macrocellular scenarios. There are other works that investigate the HO management in heterogeneous scenarios, such as small cells or femtocells scenarios [92, 93, 94, 95]. However, the HOMs have not been previously considered for fault compensation. Even if both types of algorithms (i.e., compensation and coverage optimization) tune the same parameters (e.g., HOM), in most cases, the changes made by each algorithm are different, since their objectives are different.

6.2 Problem formulation

This section analyzes a compensation method for a degraded cell that is carrying traffic even when it is affected by a fault. The degradation considered in this thesis is weak coverage that occurs when the average signal level received by users in a cell is below the minimum required level [96]. This problem may be caused by issues such as a wrong parameter configuration or wiring problems, which lead to a reduction in the eNB transmission power. Such a power reduction causes a limitation of the cell coverage area in addition to a reduction of the received signal level.

In this work, the analyzed fault is modeled as a reduction of the transmission power from the normal level (e.g., 46 dBm in macro cell [97]) to a lower level in the faulty cell. In particular, an offset representing the reduction of the transmitted power is defined. The transmission power, $PowTx$, of the faulty cell is defined as:

$$PowTx = PowTx_{max} - offset_{Tx} \, , \tag{6.1}$$

where $PowTx_{max}$ is the maximum transmission power and $offset_{Tx}$ is a configurable parameter to model different degradation levels.

6.3 System model

The system model includes control parameters and system measurements.

6.3.1 Control parameters

One of the most important effects caused by the considered problem is the limitation of the faulty cell coverage. For this reason, the most interesting parameters to take into account by the compensation algorithm are those whose modifications affect the degraded cell service area. In this work, the HOM is considered. This parameter determines the radio quality conditions for users to change their serving cell. By modifying this parameter, it is possible to control the service area of a cell.

The HO algorithm considered in this work is based on the A3 event defined by the 3GPP [97], which determines the condition that must be fulfilled to execute the HO. This condition is given by the expression

$$(RSRP_j) \geq (RSRP_i + HOM(i,j)) \,, \tag{6.2}$$

which must be satisfied for a specific time period defined by the TTT parameter. In the formula, $RSRP_i$ and $RSRP_j$ are the RSRP received by the user from cells i and j, respectively, and $HOM(i,j)$ is the HOM defined between a serving cell and each of its adjacent cells. $HOM(i,j)$ is the parameter used in the proposed compensation algorithm.

6.3.2 System measurements

To analyze the proposed compensation algorithm, a set of indicators reflecting the network performance is defined. These indicators allow to assess the effectiveness of the proposed algorithm and to determine the possible negative effects derived from the changes of configuration parameter settings.

The considered system measurements are:

- Retainability. This KPI represents the capacity of the network to maintain active connections under different radio link conditions. Thus, this indicator is related to the number of dropped calls in a cell. In this work, a dropped call occurs when a user abnormally loses its connection due to problems in the connection quality or coverage. The following expression indicates how to calculate this KPI:

$$Retainability = \frac{N_{succ}}{N_{drops} + N_{succ}} \,, \tag{6.3}$$

  where N_{succ} is the number of successfully finished connections and N_{drops} is the number of dropped connections.

- HO Success Rate (HOSR). This indicator shows the ratio of HOs that have been executed successfully, reflecting whether the HO parameters are correctly configured or there is a mobility problem in the network, e.g., a too late HO problem. It is essential to consider this KPI, since the proposed compensation algorithm is based on HOM modifications. These modifications may lead to a too late HO problem. This problem occurs when the RSRP received by a user from a certain neighboring cell is slightly higher than that received from the serving cell, but the expression 6.2 is not fulfilled. In this situation, the HO is not executed and maintaining the user connection may result in a dropped call if the RSRP from the serving cell is too low [8]. The too late HO problem appears when the HOM has high values which may occur due to the compensation algorithm modifications.

  Specifically, the HOSR can be calculated as the ratio between the number of HOs that have finished successfully and the total number of HO attempts. The latter includes all the successful HOs and the failed HOs. In this work, only the failed HOs due to a too late HO problem are considered in order to analyze the possible effect of the compensation algorithm. Formally, the HOSR can be expressed as:

$$HOSR = \frac{N_{SHO}}{N_{SHO} + N_{TLHO}} \,, \tag{6.4}$$

where N_{SHO} is the number of HOs that have been executed successfully and N_{TLHO} is the number of dropped calls due to a too late HO problem.

- 50th percentile of SINR in the downlink (SINR_{50}). This KPI represents the signal quality experienced by the user in each cell. When a weak coverage problem affects a cell, this KPI is impacted. The main purpose of the proposed algorithm is to improve this KPI. Although this fault mainly affects users in the cell edge of the faulty cell, the users in the cell center may be significantly degraded. For this reason, the 50th percentile has been selected. Thus, the group of users considered in the compensation is larger than if a lower percentile (e.g., 5th percentile) was used.

- 50th percentile of uplink throughput (ThrUL_{50}). This KPI represents the signal quality experienced by the users in the uplink. One of the possible negative effects that the proposed algorithm may produce is an uplink degradation. HOM modifications may cause that a user connected to a certain cell changes to a neighboring cell that is further. In this situation, this user may be interfered by a second user connected to the first cell. For this reason, it is important to control the uplink performance during the compensation. In this work, the maximum uplink throughput achieved by a user k is estimated based on the experienced SINR [98]. The estimation is calculated using the truncated Shannon bound formula [99]:

$$ThrUL(k) = \begin{cases} 0 & SINR(k) < SINR_{min} \\ \beta \cdot log_2(1 + SINR(k)) & SINR_{min} \leq SINR(k) \leq SINR_{max} \\ ThrUL_{max} & SINR_{max} < SINR(k) \,, \end{cases} \tag{6.5}$$

where $SINR_{max}$ and $SINR_{min}$ are SINR values where maximum and minimum throughputs are reached, respectively, $ThrUL_{max} = 514kbps$, $SINR_{max} = 14dB$, $SINR_{min} = -9dB$ and $\beta = 0.6$.

- BadRSRP. This indicator shows the number of signal level (i.e., RSRP) measurements made by users below a certain threshold (e.g., -105 dBm). This KPI identifies zones in the service area where users experience coverage problems that may avoid the connection establishment.

6.4 Cell Degradation Compensation algorithm

When a cell suffers a weak coverage problem, its users experience a reduction in the received signal quality. The aim of the compensation algorithm is to improve the quality experience of the affected users by modifying some configuration parameters of the serving and neighboring cells. In this work, the control parameter that has been modified for the faulty cell and its neighboring cells is the HOM. With these modifications, the algorithm tries to force users in the cell edge of the faulty cell to move to a neighboring cell. As a consequence, the service area of the faulty cell is reduced and its $SINR_{50}$ would be improved. Once the compensation algorithm is activated, changes applied to the HOM may have a significant impact on neighboring cells performance. These changes may produce a degradation in some KPIs, such as Retainability. For this reason, the proposed algorithm includes the Retainability from the neighboring cells as an input of the algorithm.

Fig. 6.1 shows a flowchart of the proposed methodology. Every time network KPIs are updated, a detection algorithm checks if any cell from the controlled network is affected by a failure. This functionality is out of the scope of this thesis, so that, in this work, it is assumed that a detection algorithm for detecting a weak coverage problem is implemented in the network. While there are no problems detected in the network, the collected KPIs may be used to configure the algorithm settings, some of which depend on the specific scenario. Once a weak coverage problem is detected, the compensation algorithm is activated. Firstly, a set of cells is selected in order to carry out the compensation. These cells are the six most important neighbors of the faulty cell. The level of importance is calculated based on the number of HOs executed between the faulty cell and the other cells of the network. Thus, when a faulty cell is detected, a set of 6 cells is selected based on the number of HOs. Moreover, algorithm settings can be adapted to the particular conditions of the problematic cell, e.g., the value of $SINR_{50}$ that indicates good user performance in that cell. Finally, the compensation algorithm is executed iteratively until the failure is solved. When this occurs, the compensation algorithm is deactivated and the modifications made by the algorithm have to be reverted.

The proposed compensation algorithm has been implemented by a FLC according to the Takagi-Sugeno approach [90]. Fig. 6.2 shows the main blocks of the proposed FLC.

The algorithm is executed for the faulty cell (i.e., cell i) and each of its selected neighboring cells (i.e., cell j). Thus, the inputs of the proposed FLC are the current value of $SINR_{50}$ of the faulty cell and the Retainability of the adjacent cell. Fig. 6.3 represents the membership functions defined for each FLC input. For simplicity, the selected input membership functions are trapezoidal. Thresholds related to Retainability membership function (i.e., Thr_1 and Thr_2) are set to 0.97 and 0.98, respectively, since these values are similar to the typical limits acceptable by network operators. The values used for the $SINR_{50}$ membership function (i.e., Thr_3 and Thr_4) can be adapted to on a cell basis, as radio conditions may be different. These thresholds are calculated based on the historical average (or the average value in a specific time period) of the related KPI (i.e., $SINR_{50}$) stored during normal operation of the network. In particular, Thr_4 is obtained by rounding the average value down to the nearest integer. Thr_3 is defined

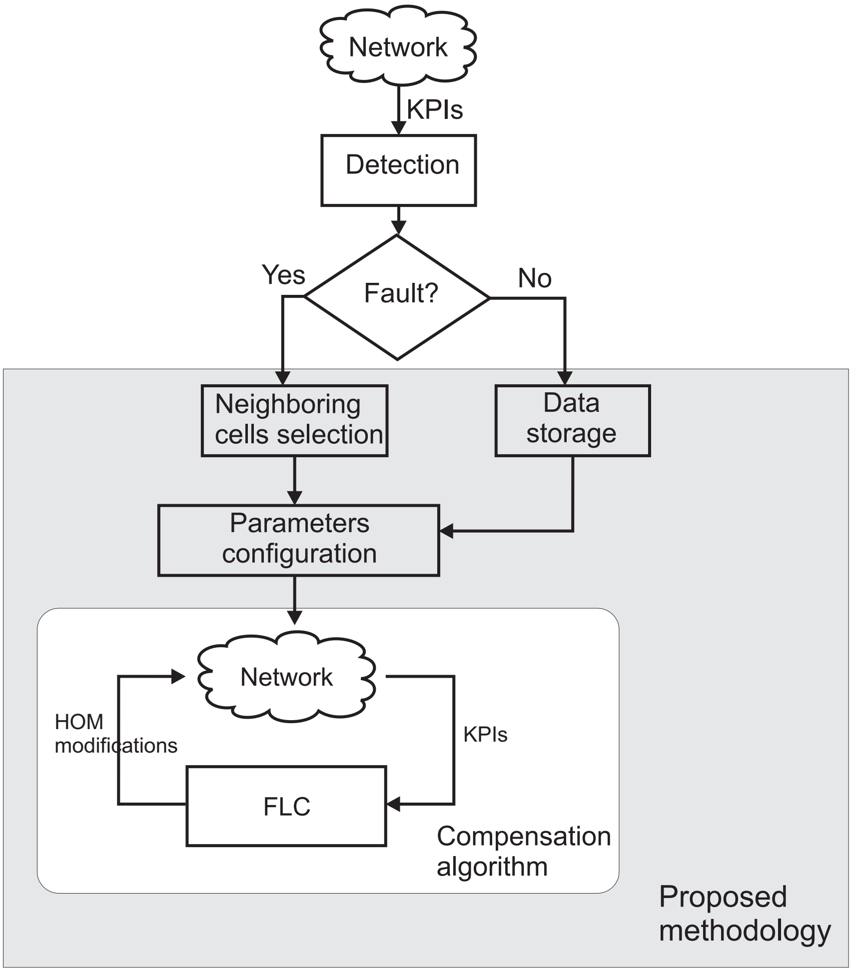

Figure 6.1: Flowchart of the proposed compensation methodology.

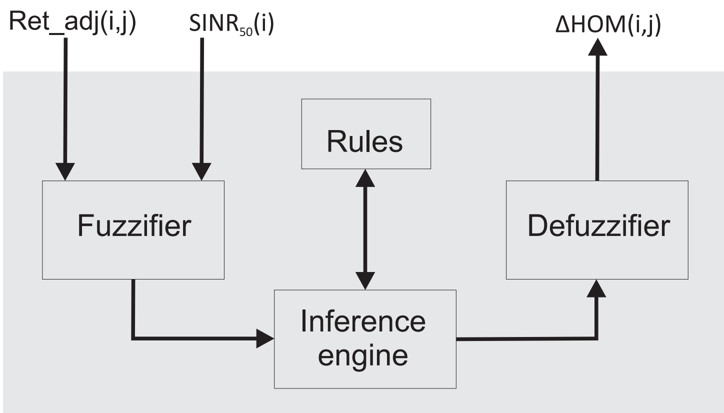

Figure 6.2: Block diagram of the proposed Fuzzy Logic Controller.

1 dB lower than Thr_4. The FLC output is the increment to be applied to the $HOM(i,j)$ per adjacency (eq. 6.2). The same change with opposite sign should be applied to the $HOM(j,i)$ to maintain the hysteresis level so as to avoid ping pong effect. Table 6.1 shows the set of rules,

where L is Low and H is High, representing the linguistic terms of the fuzzy sets, while Negative means a decrease of 1 dB, Positive means an increase of 1 dB and Null means no change in the HOM. For instance, rule no. 3 can be read as: IF (Ret_adj is high) AND ($SINR_{50}$ is low) THEN (ΔHOM is Negative). The obtained output crisp values are rounded to -1, 0 or 1 to be compatible with the 3GPP standards. In addition, the resulting HOM value is limited to avoid excessive changes or possible instabilities in mobile networks. Specifically, the HOM values are limited to [-12 12] dB. During compensation, the algorithm can stop the HOM modifications for a certain adjacency due to different situations: the current HOM value has achieved the limit value or the $SINR_{50}$ of the faulty cell achieves a high value. The latter case means that the faulty cell has achieved a similar performance to that of a normal situation. When this occurs, the $SINR_{50}$ is higher than Thr_4 and the rule 3 is activated. Without this limitation, the $SINR_{50}$ of the faulty cell would continue increasing as its service are is reduced, but the performance of the neighboring cells may drastically decrease, as the service area of latter is increased.

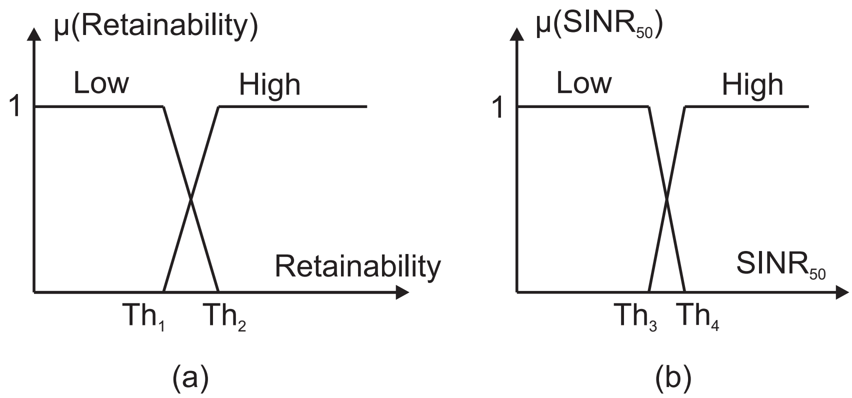

Figure 6.3: Input membership functions for (a) Ret_adj and (b) $SINR_{50}$ (dB).

Table 6.1: Fuzzy logic controller rules

No	$Ret\_adj(i,j)$	$SINR_{50}(i)$	$\Delta HOM(i,j)$
1	L	-	Positive
2	H	L	Negative
3	H	H	Null

6.5 Performance analysis

For clarity, the simulation setup is first described. Then, a preliminary sensitivity analysis is performed and performance results are presented later.

6.5.1 Simulation setup

A complete set of simulations is carried out to evaluate the proposed compensation algorithm and compare it to other approaches. Simulations are performed with the dynamic system-level simulator presented in Chapter 3. The main configuration parameters are summarized in

Table 6.2. Moreover, a function that estimates Power Control performance in the uplink is used to complete the analysis. This function is described in detail in [98].

Table 6.2: Simulation parameters

Parameter	Configuration
Cellular layout	Uniform scenario, 57 cells (19 eNBs)
	Real scenario, 75 cells (25 eNBs)
Carrier frequency	2.0 GHz
System bandwidth	1.4 MHz
Propagation model	Okumura-Hata
	Log-normal slow fading,
	σ_{sf} = 8 dB
	correlation distance=50 m
Channel model	Multipath fading,
	ETU model
Mobility model	Random direction, 3 km/h
Service model	Full Buffer, poisson traffic arrival
Base station model	Tri-sectorized antenna, SISO,
	Azimuth beamwidth=70°
	Elevation beamwidth=10°
	$P_{TX_{max}}$ =43 dBm
Scheduler	Time domain: Round-Robin
	Freq. domain: Best Channel
Handover	Triggering event = A3
	Measurement type = RSRP
	Initial HOM = 2, 3 dB
	TTT = 100 ms
	ping-pong period = 5 s
Radio Link Failure	$SINR < -6.9\ dB$
	for 500 ms
Time resolution	100 TTI (100 ms)

Firstly, a preliminary study is carried out to check the potential of the proposed compensation methodology, based on HOM modifications, for the weak coverage failure. In these first simulations, the uniform scenario is considered and a value of 10 dB is selected for the parameter $offsetTx$, as described in Section 6.2. Fig. 6.4 shows the RSRP level of the serving cell in each point of the scenario when the fault occurs. The circle indicates the faulty area. In such a regular scenario, a comparison is carried out between several compensation methods, namely HOM modifications (HOM), antenna tilt modifications (TILT) and a combination of both approaches (HOM+TILT).

In the rest of simulations, the aim is to quantify the gain of the proposed compensation algorithm when a weak coverage fault in the live network. For this purpose, the realistic scenario shown in Fig. 6.5 is considered. Fig. 6.5(a) shows the scenario in a normal situation (i.e., no faults in the network). In addition, a circle indicates the considered cells for the statistics. The remaining cells of the scenario are not considered in the results to avoid border effect. On the

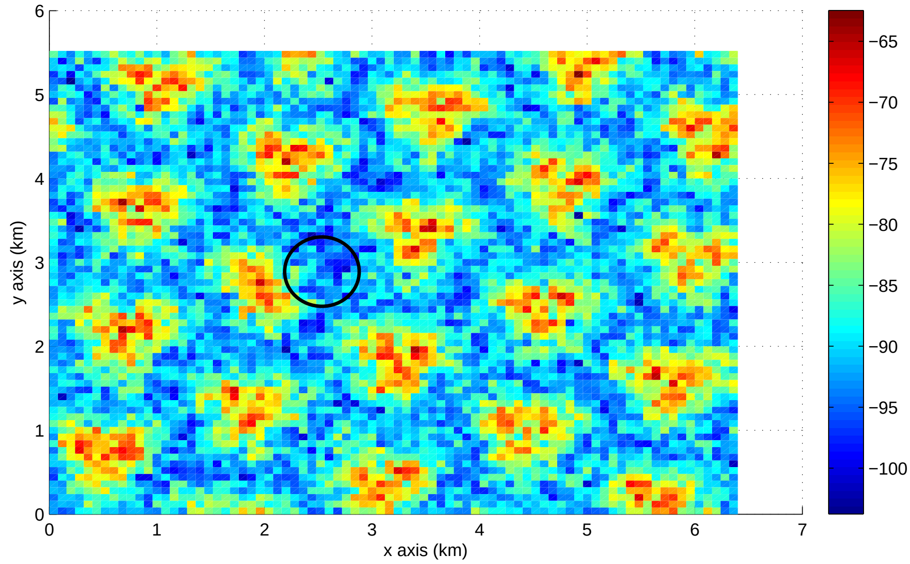

Figure 6.4: Average RSRP level from serving cell in the uniform scenario (dBm) in the fault situation.

other hand, Fig. 6.5(b) presents the scenario when a weak coverage fault is affecting cells 10, 11 and 12. The location of the faulty site is shown in the figure. It can be seen that this fault produces a reduction in the coverage area of the faulty cells.

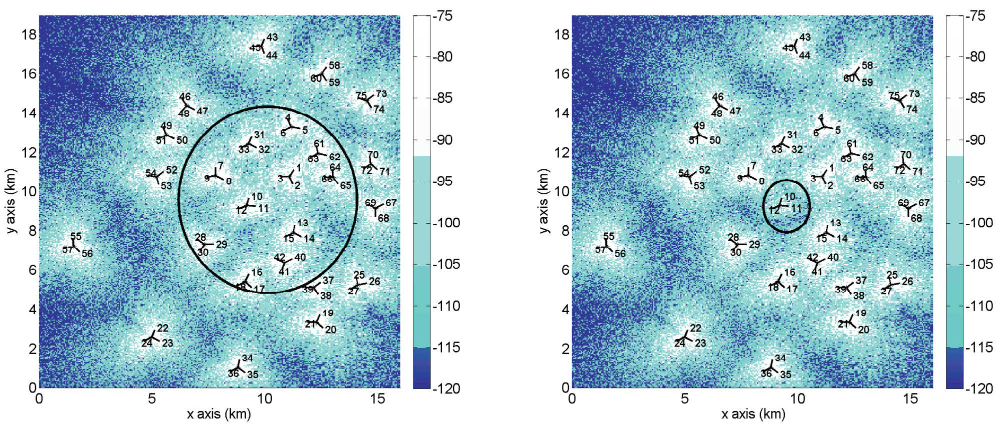

Figure 6.5: Average RSRP level from serving cell in the realistic scenario (dBm): (a) Normal situation and (b) Faulty situation.

In the realistic scenario, a first set of simulations aims to show the basic performance of the algorithm, including a detailed analysis of different aspects of the algorithm behavior. In addition, a comparison to other approaches is presented in the same subsection to clarify the differences between compensation methods. In particular, different strategies based on antenna tilt modifications are considered. For these simulations, the weak coverage fault is configured with a value of 10 dB for the $offsetTx$ parameter.

Then, a second set of simulations is carried out to analyze the algorithm performance in different situations. These tests include different levels of degradation in the faulty cell, scenarios with different user mobility conditions, different baseline configuration, different algorithm internal settings or several faulty cells simultaneously. In general, all simulations consist of the same phases. The first phase presents the normal operation of the network (i.e., no faults occur). The second stage presents the network performance when the weak coverage fault occurs in one or several cells. During this phase, the faulty cell suffers a reduction of the transmission power, but the compensation algorithm is not activated yet. Finally, in the third phase, the compensation algorithm is activated. Each simulation comprises 30 simulation loops in total (3 simulation loops of normal situation, 2 simulation loops of faulty situation and 25 simulation loops of compensation). Each simulation loop corresponds to an hour of network performance. The duration of each simulation loop is selected to guarantee that the indicators are statistically stable. However, these times can be reduced when the algorithm is applied to a real network. In this case, the limitation is the periodicity of updating the KPIs that are used as inputs of the algorithm. This periodicity can be less than an hour (e.g., 15 minutes) so that the total time to achieve a compensation situation can be reduced.

The main figures of merit to compare the methods are $SINR_{50}$ and Retainability. Unless stated otherwise, the values of interest are those obtained at the end of the compensation process.

The following subsections present the results obtained in the different tests. The detailed configuration parameters, such as the considered faulty scenario and the specific algorithm and network settings, are described for each simulation case.

6.5.2 Results

Preliminary study

This first set of simulations analyzes the compensation of a weak coverage failure in a uniform scenario. The analysis includes three approaches based on HOM and antenna tilt modifications: HOM, TILT and HOM+TILT. The aim of changes is to reduce the service area of the problematic cell by forcing users located in the cell edge to change to a neighboring cell, to improve the service quality of the affected users. Specifically, the antenna tilt is modified from 5° (i.e., default value) to 12° for the faulty cell with a step of 1°. In the case of the HOM, the parameter is modified from 3 dB (i.e., default value) with a step of 1 dB. The modification of the HOM is symmetric in each adjacency to maintain a hysteresis value and avoid the HO ping-pong.

Fig. 6.6 and Fig. 6.7 show $SINR_{50}$ and Retainability values obtained at the end of the compensation process for the faulty cell, the average value of the neighboring cells and the average value of the rest of cells. From the SINR values in Fig. 6.6, it is deduced that only the methods based on HOM modifications (i.e., HOM and HOM+TILT) achieve a significant improvement of signal quality, while the method based on tilt modifications (i.e., TILT) cannot improve signal quality in the faulty cell. Regarding Retainability, shown in Fig. 6.7, the methods based on tilt modifications (i.e., TILT and HOM+TILT) obtain the best results, although the results obtained with the HOM method are also acceptable. From these results, it can be concluded that, in this scenario, the proposed method (i.e., HOM) is competitive with the best of methods (i.e., that combining the modification of both parameters, HOM+TILT).

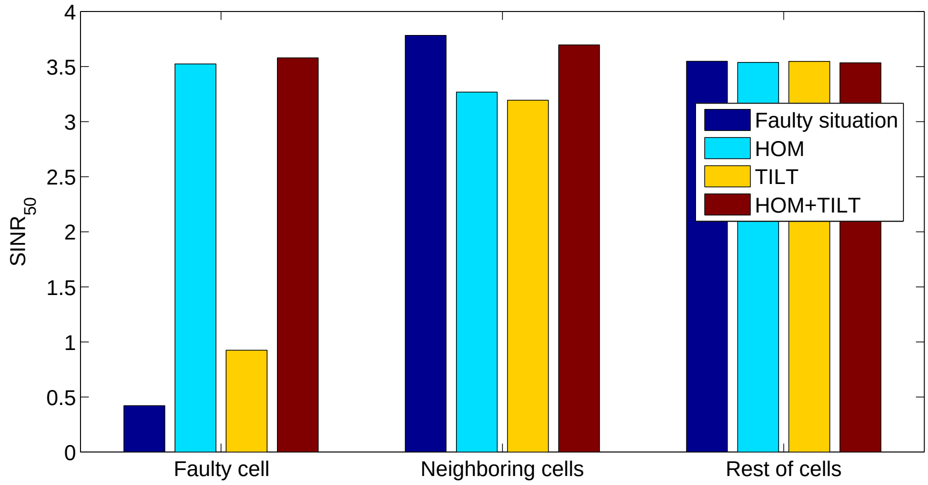

Figure 6.6: $SINR_{50}$ (dB).

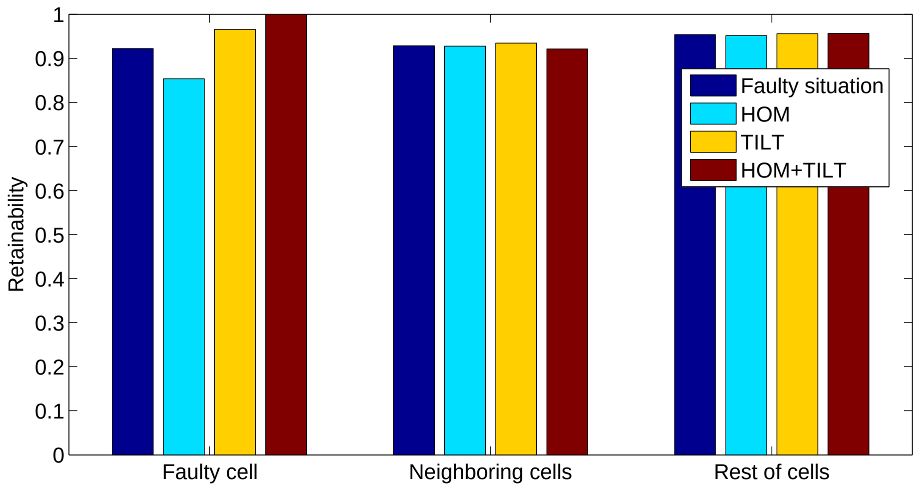

Figure 6.7: Retainability.

Algorithm performance

The following paragraphs describe the results of experiments carried out in the live scenario to assess the proposed algorithm (based on changing HOM).

A. Basic performance

In this first test, the basic performance of the proposed algorithm is presented. As a first step, it is necessary to select the cell that is going to suffer the weak coverage fault. For this purpose, an analysis of the $SINR_{50}$ and $ThrUL_{50}$ values on a per-cell basis is carried out. Fig. 6.8 and Fig. 6.9 show $SINR_{50}$ and $ThrUL_{50}$ values for each cell in a normal situation. Although the scenario consists of 75 cells, only the value of 33 cells are considered for statistics. It can be seen that there is diversity in the values.

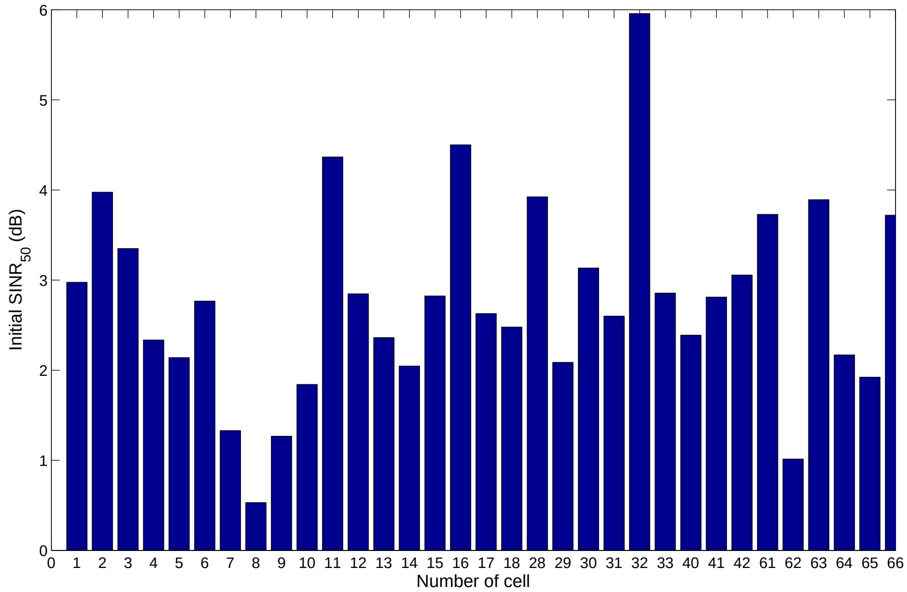

Figure 6.8: 50th percentile of the SINR in a normal situation.

In this work, cell 11 is selected as faulty cell. Since it is located in the center of the scenario, it allows to analyze the proposed compensation algorithm avoiding border effect. However, it can be seen that, for the selected faulty cell, the values of $SINR_{50}$ and $ThrUL_{50}$ of the neighboring cells are low. There are several cells that could be selected as faulty cells avoiding border effect (cells located in the center of the scenario) but the average value of $SINR_{50}$ and $ThrUL_{50}$ of the neighboring cells in these cases are very similar.

As described in Section 6.4, the first stage of the compensation method is to select the neighboring cells in charge of the compensation and to obtain the algorithm settings. Compensating neighbors are obtained from the number of HOs executed between cell 11 and the remaining cells of the scenario in the normal situation. In this case the selected cells are: 2, 3, 10, 12, 13 and 15. In Fig. 6.5, it can be checked that these cells correspond to the first tier of neighboring cells of the faulty cell. Algorithm settings are calculated from the $SINR_{50}$ statistics in the first simulation loops (i.e., normal situation), as described in Section 6.4. Table 6.3 summarizes the algorithm settings used in this test.

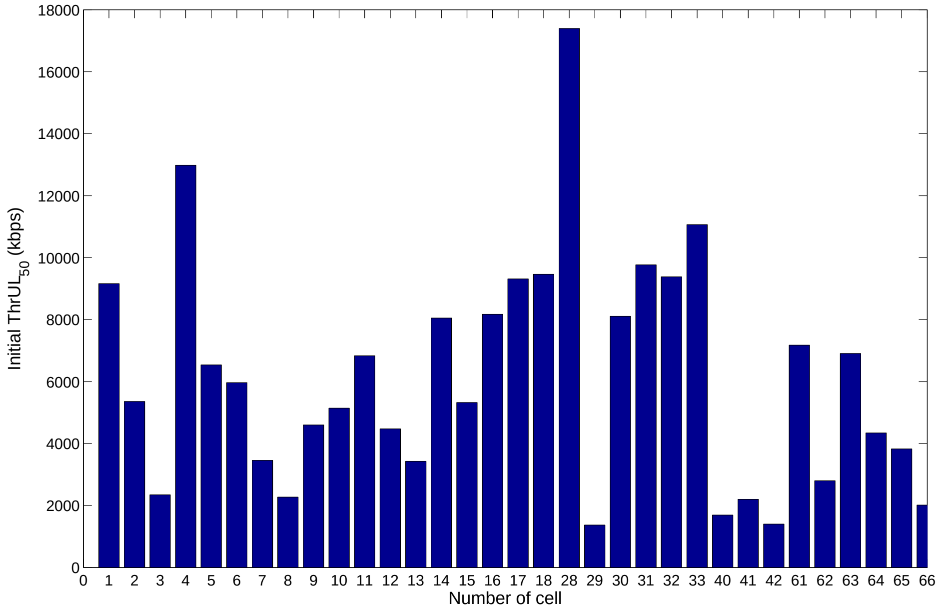

Figure 6.9: 50th percentile of ThrUL in a normal situation.

Table 6.3: Algorithm settings

Parameter	Configuration
Th_1	0.97
Th_2	0.98
Th_3	2
Th_4	3

Fig. 6.10 and 6.11 present the results of the algorithm by showing the time evolution of $SINR_{50}$ and statistics. The curves correspond to the faulty cell KPI values and the average value of neighboring cells. In Fig. 6.10(a), it can be observed that, when the fault occurs (simulation loops 4 and 5), the $SINR_{50}$ of the faulty cell suffers an important degradation. Once the compensation algorithm is activated and HOM modifications begin (simulation loops 6 and thereafter), $SINR_{50}$ increases, reaching values similar to those of the normal situation. At the same time, the algorithm keeps the $SINR_{50}$ of neighboring cells without degradation.

A possible undesired effect might be a degradation in the uplink of the neighboring cells, since the changes made by the compensation algorithm cause an increase of the service area of the neighboring cells. Along the simulation loops, HOM changes cause that users from the faulty cell are re-assigned to a neighboring cell. These users are farther than other users of the neighboring cell, which translates into an increase of service area. Such an increase may affect the uplink performance, since these users may be interfered by the users from the faulty cell. Fig. 6.10(b) shows that, the proposed algorithm achieves a compensation situation without degrading the uplink of the neighboring cells. Fig. 6.10(b) shows how $ThrUL_{50}$ in the faulty cell is increased due to a coverage area reduction by new HOM values, while $ThrUL_{50}$ for the

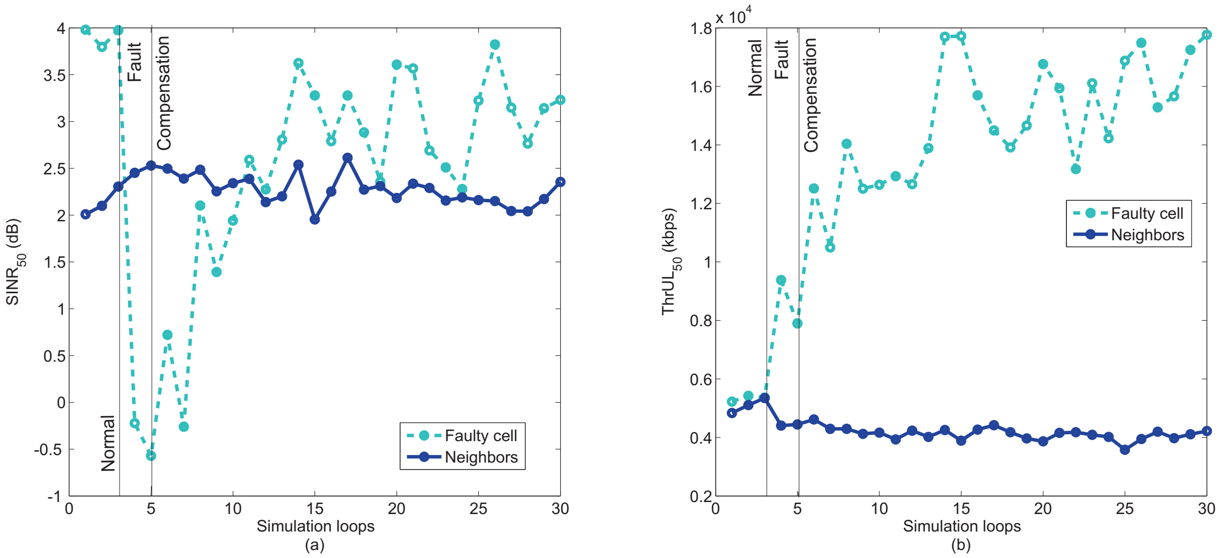

Figure 6.10: Basic performance: (a) SINR$_{50}$ (dB) and (b) ThrUL$_{50}$ (kbps).

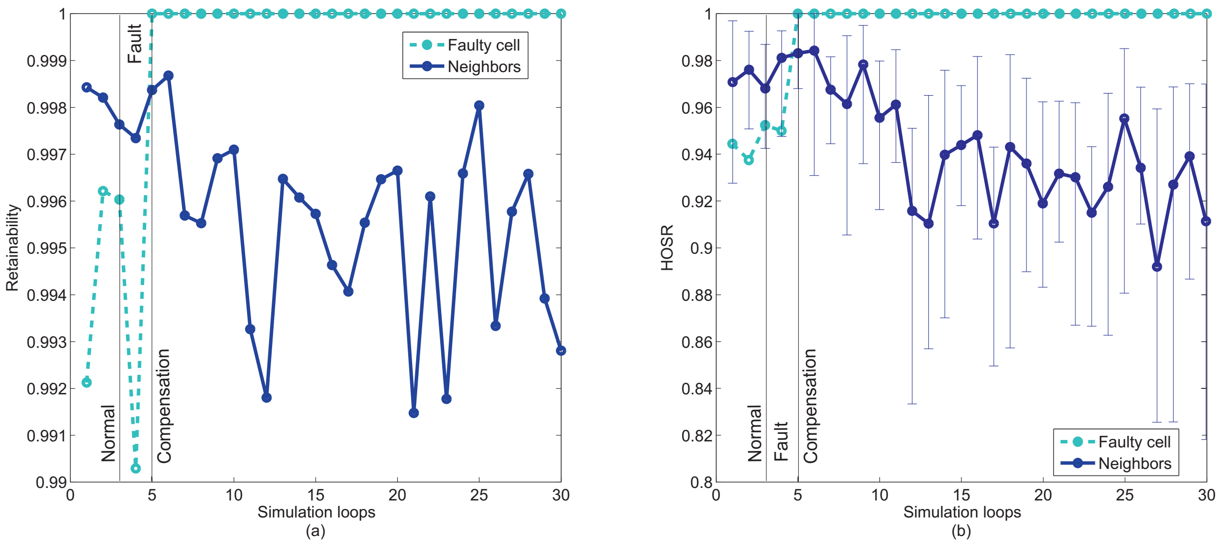

Figure 6.11: Basic performance: (a) Retainability and (b) HOSR.

neighboring cells remains stable, despite the increase of their service areas.

Fig. 6.11(a)-(b) present the time evolution of Retainability and HOSR, respectively. It can be seen that both Retainability and HOSR values for the neighboring cells suffer a slight degradation, but the final value remains in an acceptable level.

For completeness, Fig. 6.11(b) includes error bars to show the variability of HOSR measurements across different simulations. Such a ratio is the only indicator that is not statistically stable due to the simulated scenario, where few HO attempts take place. To quantify this variability, a set of 20 simulations is carried out with the same setup. Error bars represent the 5th and 95th percentile of HOSR measurements in each iteration. It can be observed that, even if the minimum HOSR value is 0.82, the average value is higher.

As remarked in Section 6.3, the fault considered in this work mainly affects users in the cell edge of the faulty cell. Although the proposed algorithm uses the 50th percentile as an input, it is also important to consider other percentiles to analyze the impact of the fault on other groups of users (e.g., users in the cell edge or near the base station). Thus, if a 5th percentile of SINR is considered, the analyzed information is related to the group of users that presents the worst quality performance in a cell. Usually, these users are located in the cell edge. Conversely, when a high percentile (e.g., 95th) is selected, the information provided is related to users with the best quality performance. These users are usually located near the base station. Finally, the 50th percentile (i.e., the percentile used as input of the algorithm) provides information about users with a performance near the average.

Fig. 6.12 presents the 5th, 50th and 95th percentile of SINR when a reduction of 10dB in the base station transmission power is considered. Firstly, it can be seen that the fault affects users in all zones of the cell, as the three percentiles present degradation when the fault occurs. In this work, the improvement of the 50th percentile is the objective of the compensation algorithm. For this reason, this indicator achieves, after the compensation, similar values to that of the normal situation. The compensation algorithm does not have a significant effect in the 95th percentile because HOM changes mainly affect users in the cell edge. In fact, Fig. 6.12 shows that the values of the 5th percentile at the end of the compensation process are higher than that of the normal situation. Therefore, although the proposed algorithm uses the 50th percentile as an input, the cell edge of the faulty cell is also improved.

In summary, the weak coverage fault causes a degradation in the $SINR_{50}$ of the faulty cell, which was successfully overcome by the proposed method, without degrading neighboring cells.

The analysis is completed with a comparison of different compensation approaches in the realistic scenario. The considered method for the comparison is based on tilt modifications since it is the method most frequently used for outage compensation. The initial antenna tilt angle of the selected cells (i.e., cell 11 as faulty cell and cells 2, 3, 10, 12, 13 and 15 as neighbors) are 2°, 4°, 2°, 5°, 4°, 5° and 4°, respectively. The step used in the simulations is 1° because bigger values may produce significant variations in the KPIs. The minimum angle is limited to 0° in order to avoid negative values of the tilt angle. Several simulations have been executed in order to analyze different combinations of tilt changes for the faulty cell and the neighboring cells. The strategy that obtains the best results is based on downtilting neighboring cells (DN). Moreover, two additional compensation methods based on tilt modifications are tested. In particular, an approach based on uptilting neighboring cells (UN) and a method based on downtilting the faulty cell (DF).

Fig. 6.13 shows the results obtained for the tilt compensation methods and the proposed algorithm (HOcomp). DN method allows to improve $SINR_{50}$ of the faulty cell. With DN, the final achieved antenna tilt angle is 12° for all compensating cells. Downtilting neighbors produce an interference reduction in the faulty cell and allow to increase the $SINR_{50}$ even when it is accepting more users from the neighboring cells. The reason for that is that the experienced

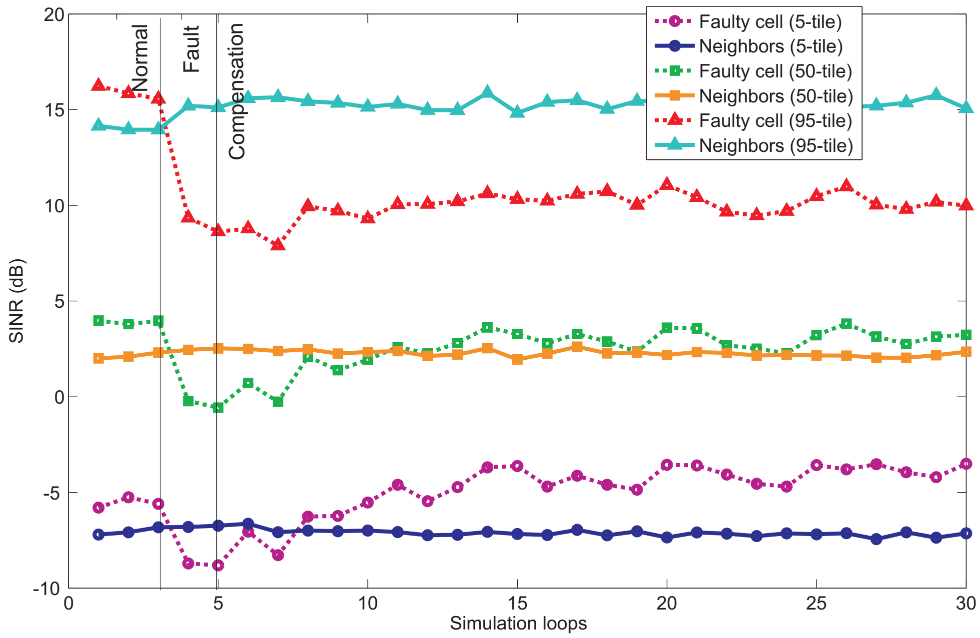

Figure 6.12: 5th, 50th and 95th percentiles of SINR in a weak coverage fault situation.

quality in the cell edge of the faulty cell is improved. However, the HOcomp method achieves a higher value of the $SINR_{50}$, which is more similar to the normal situation. Specifically, the HOcomp method achieved a 33.1% of improvement compared to the DN method. In addition, the DN method presents a negative effect in the cell edge of the neighboring cells which is reflected by a reduction of the $ThrUL_{50}$. On the other hand, the HOcomp method presents a lower value of the HOSR although it remains above 95%. Based on the obtained results, it can be concluded that the HOcomp and DN methods have a similar behavior (although the HOcomp method achieves a better result).

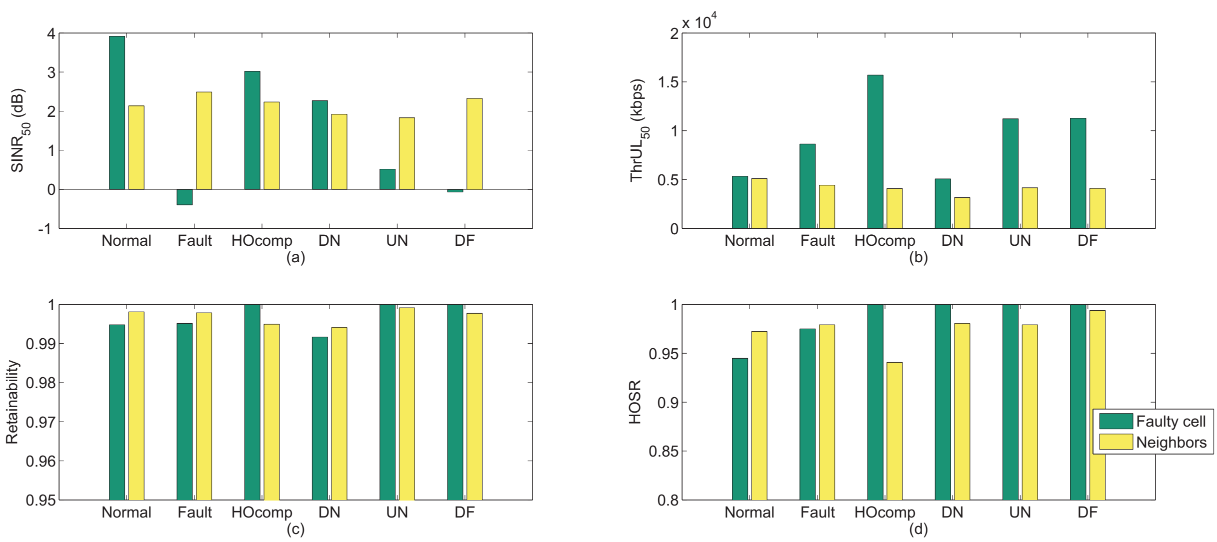

Figure 6.13: Comparison results: (a) $SINR_{50}$ (dB), (b) $ThrUL_{50}$ (kbps), (c) Retainability and (d) HOSR.

DN presents an important disadvantage, downtilting several neighboring cells at the same time may generate coverage holes. Note that DN algorithm increases the service area of the faulty cell which is the opposite effect to that obtained with the proposed algorithm. Conversely, a reduction of the service area of the faulty cell can be obtained uptilting neighbors (i.e., UN method). This strategy is usually applied to outage problems. However, it is observed in Fig. 6.13 that this approach does not achieve a $SINR_{50}$ improvement, since the interference in the faulty cell is also increased, as the interfering antennas point towards the service area of the faulty cell and the traffic load of interfering neighbors is higher.

Another option to reduce the coverage area of the faulty cell is to increase its antenna tilt (i.e., DF method). Signal quality of the neighboring cells can be improved by downtilting the faulty cell antenna because the interference produced by the faulty cell can be reduced. However, the expected improvement is small, since the transmission power of the faulty cell has been reduced by the fault, so that the interference level produced in the neighboring cell is small too. In addition, when the faulty cell antenna tilt is increased, a deterioration of the cell edge of the faulty cell may be caused so that the $SINR_{50}$ of the faulty cell cannot be increased (Fig. 6.13). For a more detailed analysis, Fig. 6.14 shows the 5th, 50th and 95th percentile of the SINR of the faulty cell and the neighboring cells when the DF method is applied. It can be seen that this approach does not achieve any improvement in the SINR of the faulty cell, so that it is not an alternative to compensate the fault.

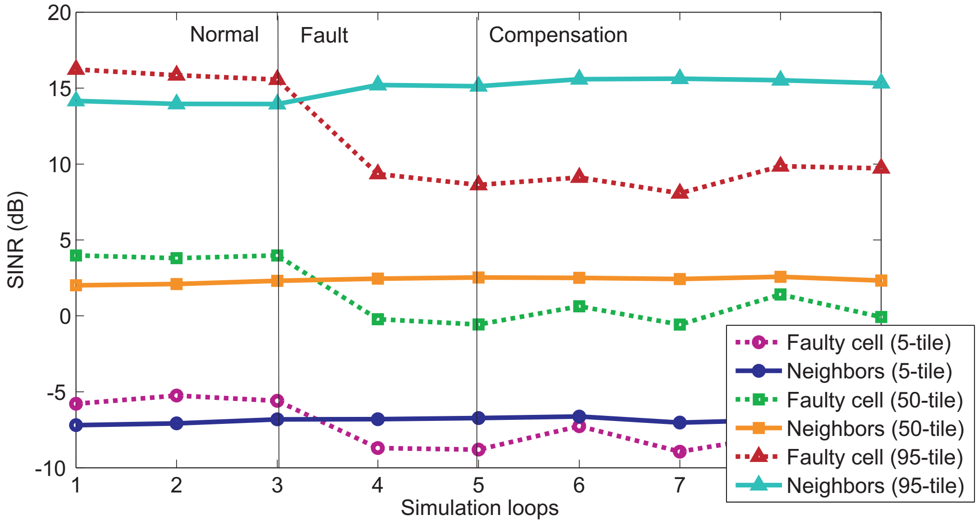

Figure 6.14: Comparison results: 5th, 50th and 95th percentile of the SINR of the faulty cell (dB).

B. Impact of the magnitud of degradation

In this test, the proposed algorithm is evaluated for different levels of degradation. For this purpose, several values for the $offsetTx$ parameter are defined in order to implement different levels of degradation. Specifically, the simulations are carried out with values of 7 dB (Fault case 1), 10 dB (Fault case 2) and 13 dB (Fault case 3). Fig. 6.15 and 6.16 show the results obtained in the simulations. Specifically, Fig. 6.15(a) shows the $SINR_{50}$ temporary evolution for the different degradation levels.

As expected, the higher level of degradation (i.e., Fault case 3) causes the most significant reduction in the $SINR_{50}$ during the fault stage. However, once the compensation algorithm is activated, an improvement of this KPI is obtained for all the simulated levels of degradation. The final $SINR_{50}$ value achieved by the algorithm is similar to that obtained in the normal situation, except for Fault case 3, which is a bit lower. The final value of the HOM achieved by the algorithm is different depending on the degradation level. In particular, the compensation situation for Fault case 1 is achieved for a minimum $HOM(i,j)$ value of -5 dB. However, in the Fault case 3 a $HOM(i,j)$ equal to -12 dB (i.e., the minimum allowed value) is needed to successfully compensate the fault. For the Fault case 2 the minimum $HOM(i,j)$ value obtained in the compensation stage is -7 dB.

The rest of the considered KPIs (i.e., $ThrUL_{50}$, HOSR and Retainability) in the neighboring cells are not degraded much by the compensation actions.

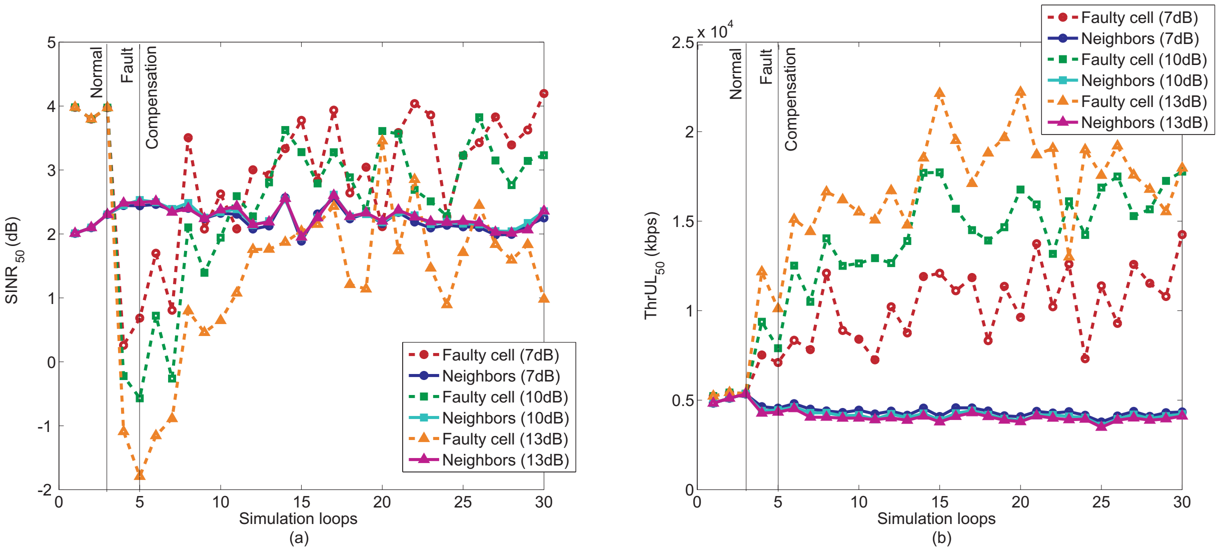

Figure 6.15: Results for different degradation levels: (a) $SINR_{50}$ (dB) and (b) $ThrUL_{50}$ (kbps).

C. Impact of initial network state

As described before, the initial values of $SINR_{50}$ and $ThrUL_{50}$ for the selected neighboring cells are low. New simulations are performed to obtain differences in the initial $SINR_{50}$ and $ThrUL_{50}$ values. Specifically, the users distribution is modified to slightly improve the performance of the neighboring cells. For this purpose, the number of users generated is decreased compared to the default configuration. Fig. 6.17 below shows that the proposed algorithm achieves similar qualitative performance regardless the initial $SINR_{50}$ value.

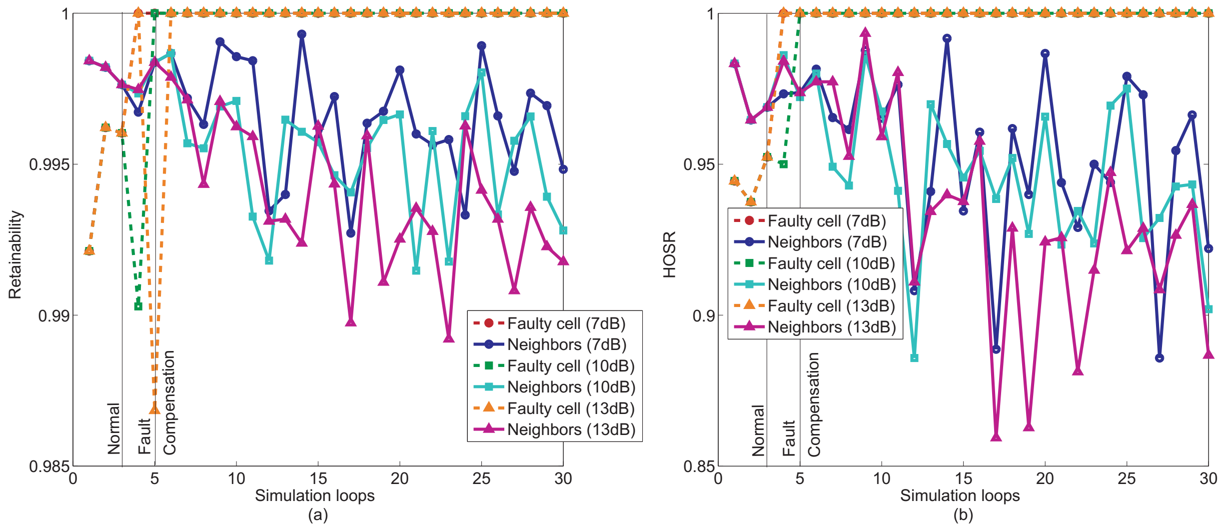

Figure 6.16: Results for different degradation levels: (a) Retainability and (b) HOSR.

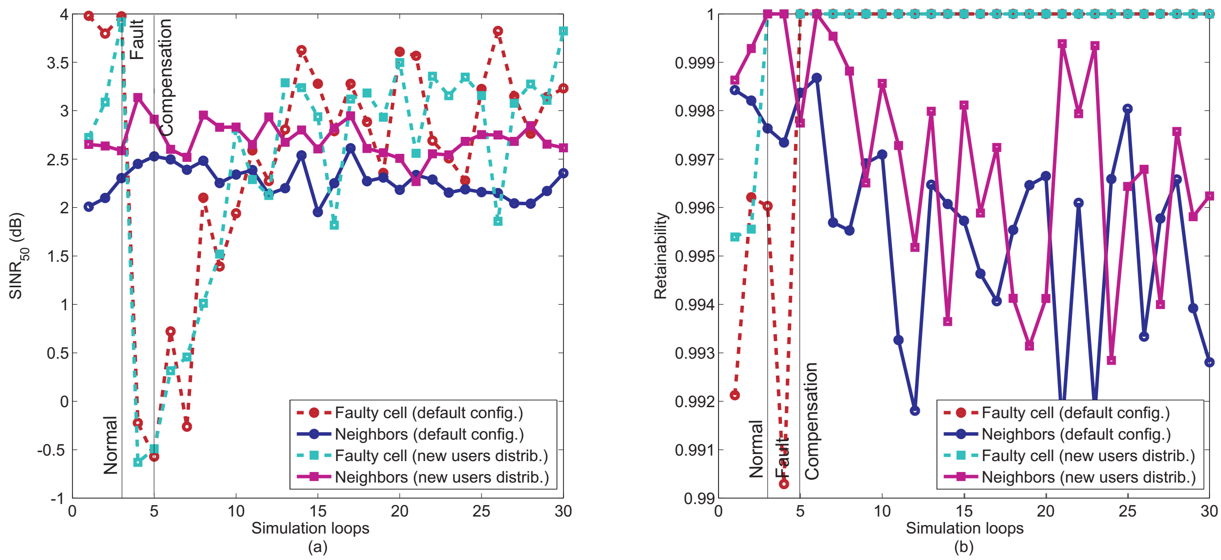

Figure 6.17: Results for different users distribution: (a) SINR_{50} (dB) and (b) Retainability.

D. Impact of HOM limits

As described in Section 6.4, some rules are included in the algorithm to limit the HOM modifications to avoid that the performance of the neighboring cells gets worse as a consequence of the compensation actions. To illustrate the situation when no limit are applied to the proposed algorithm, new figures are presented. Fig. 6.18 and 6.19 show the network performance when consecutive HOM modifications are applied to a weak coverage problem with no limitations. The network performance when the proposed algorithm is activated is also included in the figures. Specifically, Fig. 6.18(a) shows that when no limits are applied to the HOM modifications the final SINR_{50} value of the faulty cell is higher than the one achieved by the method with limits. However, Fig. 6.19 shows the consequences of not having limits in the HOM modifications. In this case, both Retainability and HOSR suffer an important degradation compared to the method with limits. The proposed algorithm with limits achieves similar $SINR_{50}$ values to those of the normal situation, while not degrading the neighboring cells performance.

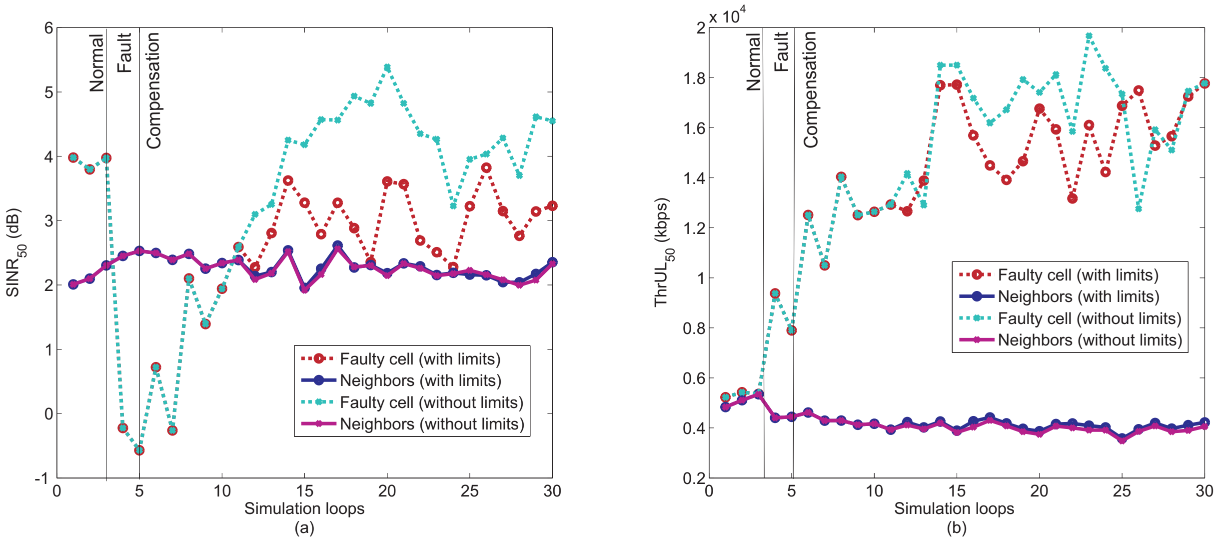

Figure 6.18: Results without limits to *HOM* modifications: (a) $SINR_{50}$ (dB) and (b) $ThrUL_{50}$ (kbps).

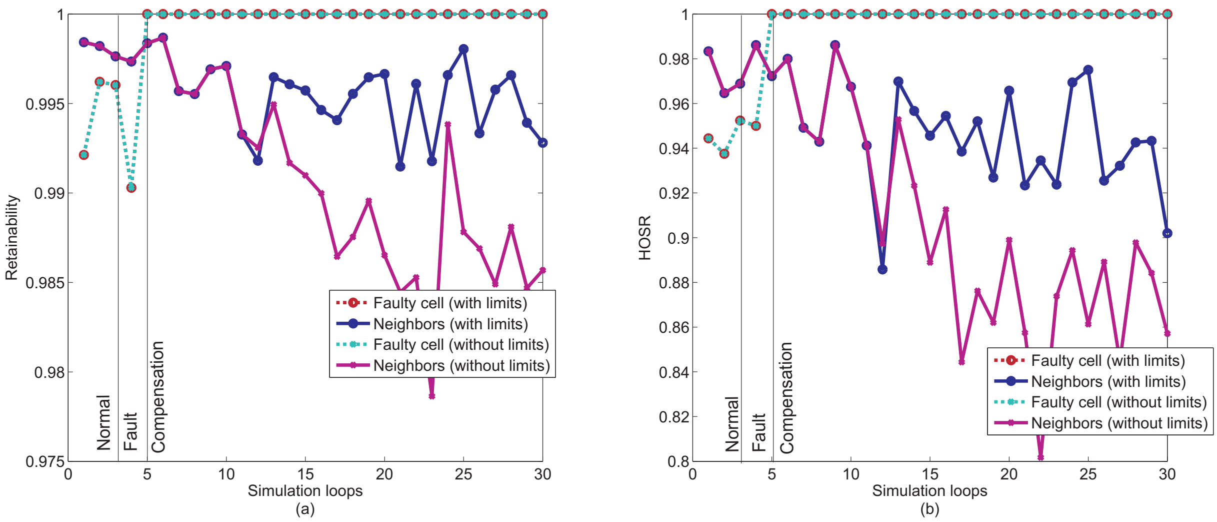

Figure 6.19: Results without limits to *HOM* modifications: (a) Retainability and (b) HOSR.

E. Impact of user mobility

This set of tests aims to evaluate the proposed algorithm under different user mobility conditions. The user mobility model included in the simulator works as follows. When a new user is created, a random direction is calculated and assigned to this user. Along the simulation steps, the user moves in the assigned direction and the configured speed. The mobility model takes into account the scenario boundaries. In this work, it is not necessary to have a more realistic model because it is applied on an outdoor scenario where user trajectories have a high random component, making them hard to predict in comparison to indoor scenarios. In this case, it is enough that users can move along the scenario and perform HO between different cells. In other scenarios, such as small cells or femtocell indoor scenarios, the mobility model is more critical. The tests presented in this subsection consider different user speeds (i.e., 3 and 50 km/h). The selected cells and the algorithm settings are the same as those considered in the basic performance analysis.

The obtained results are presented in Fig. 6.20 and 6.21. Both figures show the temporary evolution for the selected KPIs along the three simulated stages. In Fig. 6.20, the experienced signal quality both in uplink and downlink is presented. Fig. 6.20(a) shows the $SINR_{50}$ evolution for the faulty cell and the average value for the neighboring cells. The proposed algorithm works in a similar way independently of the user speed. In both cases, a compensation situation is achieved with a similar $SINR_{50}$ performance to that of the normal situation without degrading the experienced quality in the neighboring cells. The main difference between the two simulations is that such a similar compensation situation is achieved for different values of HOM. When the user speed is configured to 3 km/h a higher HOM reduction is needed. Specifically, the $HOM(i,j)$ achieved for 3 km/h is -7 dB and for 5 km/h, -5 dB. Regarding uplink, Fig. 6.20(b) shows the $ThrUL_{50}$. It can be seen that the changes made by the compensation algorithm do not decrease the throughput experienced by the users in the neighboring cells.

Fig. 6.21(a) and (b) present Retainability and HOSR for the faulty and the neighboring cells. Fig. 6.21(a) shows that the Retainability behavior for both user speeds is quite similar. Although the faulty cell with a user speed of 50km/h presents a slight degradation, the smallest value is near 98%. Analyzing the results obtained for HOSR, it may seem that when the user speed is 3 km/h, the HOSR suffers an important degradation. However, it is not possible to compare the HOSR results for the two considered user speeds. The reason for that is related to the HOSR definition presented in Section 6.3. HOSR depends on the total number of HOs executed in each cell. One of the main differences in the obtained results for different user speeds is that, when the users move faster, the number of HOs increases, so that the number of failed HOs is less significant.

F. Impact of multiple faulty cells

This subsection includes three different cases. In all three cases, more than one cell suffers from the weak coverage fault at the same time. In a first scenario, the weak coverage problem affects the three cells of a tri-sectorized site, but cell overlapping with neighbors is still high enough not create a coverage hole (referred to as cosited faulty cells without coverage problem). In a second scenario, antenna tilts of both faulty cells and neighbors are modified so that a coverage hole is created by the weak coverage in the site (referred to cosited faulty cells with coverage problem). In a third scenario, the weak coverage problem affects cells of different sites (referred to as non-cosited faulty cells).

In the first scenario, a whole site (cells 10, 11 and 12) is affected by the analyzed fault. When more than one cell is affected, the algorithm firstly selects the most important neighboring cells

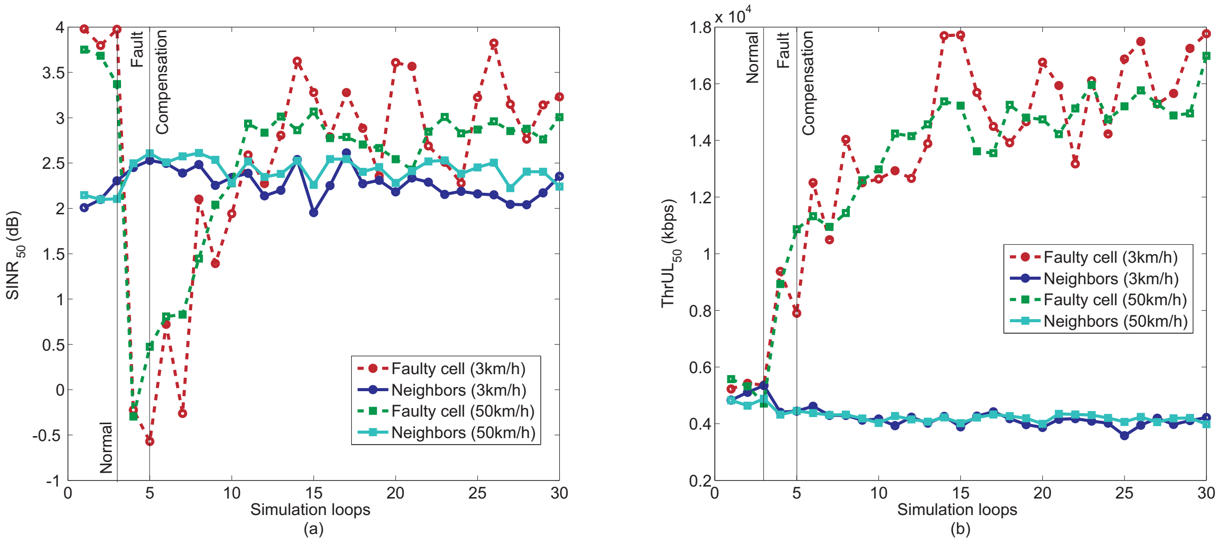

Figure 6.20: User mobility simulation results: (a) $SINR_{50}$ (dB) and (b) $ThrUL_{50}$ (kbps).

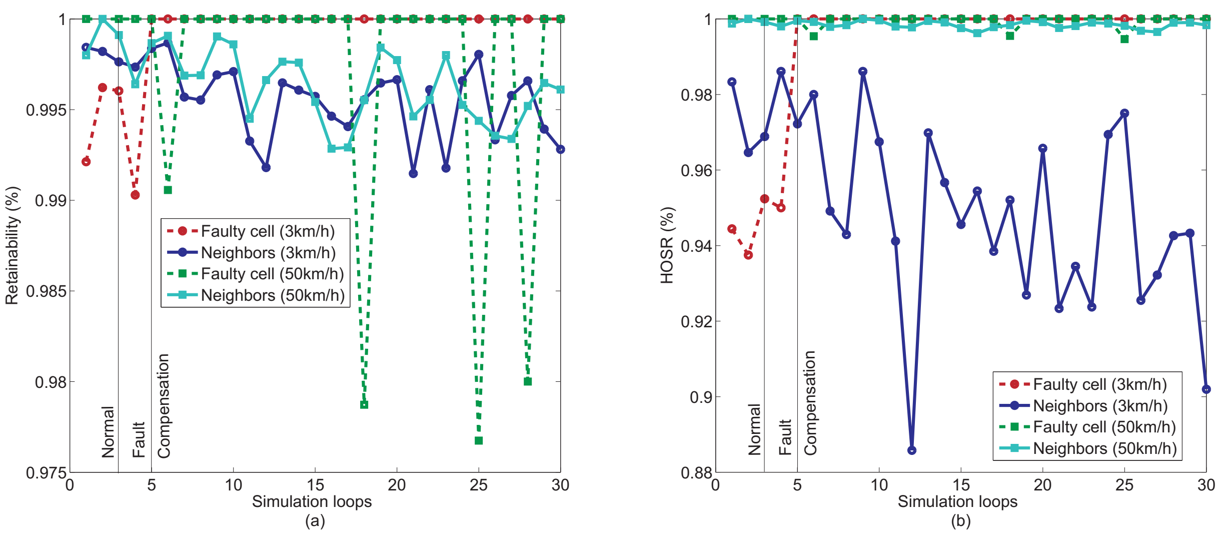

Figure 6.21: User mobility simulation results: (a) Retainability and (b) HOSR.

for each faulty cell. In this case, the selected neighboring cells are: 3, 8, 11 and 12 for cell 10; 2, 3, 10, 12, 13 and 15 for cell 11; and 8, 9, 10, 11, 28 and 29 for cell 12. Then, the selected neighboring cells that are suffering from the fault are discarded. Thus, the faulty site consists of cells 10, 11 and 12 and the definitive list of compensating cells are: 2, 3, 8, 9, 13, 15, 28 and 29. The following step of the algorithm is to select the algorithm settings. In this test, different algorithm settings are calculated for each faulty cell. Table 6.3 shows the algorithm settings obtained for cells 11 and 12. For cell 10, the thresholds related to the $SINR_{50}$ membership function take different values (i.e., Thr_3=1 and Thr_4=2), since the observed value in the normal stage are slightly smaller than for the other cells.

Fig. 6.22 depicts the average performance values measured for the three faulty cells and their neighboring cells in each of the three phases of the test (normal operation, fault and end of compensation). In this case, the obtained results are similar to those obtained in previous tests. Fig. 6.22(a) shows the $SINR_{50}$ values, which are degraded when the fault occurs and later improved when the compensation is made. The price to be paid is a slight reduction in the $SINR_{50}$ of the neighboring cells. Fig. 6.22(b) shows the $ThrUL_{50}$ results. As previously mentioned, the $ThrUL_{50}$ experienced by the users of the faulty cell increase significantly due to the coverage area reduction caused by the fault. During the compensation stage, neighboring cells do not show a significant degradation of the uplink so that the negative effect caused by the compensation algorithm in the neighboring cells is very limited. Fig. 6.22(c) and (d) present the results for Retainability and HOSR, respectively. In both cases, it is observed that the behavior of both KPIs is similar in the three stages of the simulation. Only the value of the HOSR of the neighboring cells presents a slight degradation. The minimum values achieved for the HOM are -4 dB for cell 10, -7 dB for cell 11 and -5 dB for cell 12.

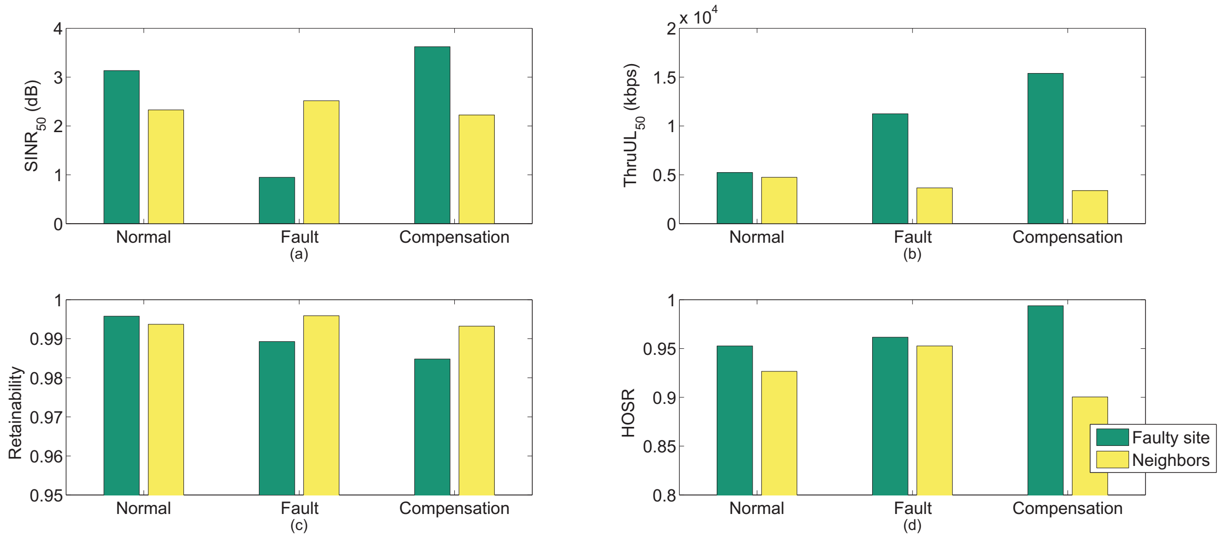

Figure 6.22: Results for cosited faulty cells without coverage problem: (a) $SINR_{50}$ (dB), (b) $ThrUL_{50}$ (kbps), (c) Retainability and (d) HOSR.

When a whole site is affected by the weak coverage fault, other effects, in addition to the SINR degradation, may appear in the network such as a coverage hole. To analyze this situation, a different simulation is carried out. In this case, the antenna tilt of the cells under study (i.e., the faulty site and the compensating cells) is set to 7° to produce coverage holes when the weak coverage fault occurs. In this test, it is important to check the BadRSRP indicator, which provides information about users without coverage. Fig. 6.23 and Fig. 6.24 show the results obtained with the different compensation approaches: the proposed method (i.e., HOcomp), a method based on uptilting the neighbors (i.e., UN method) and a combination of both (i.e., UN+HOcomp). Firstly, it can be seen that the HOcomp method is able to improve the $SINR_{50}$ of the faulty cell, although the BadRSRP of the neighboring cells remains degraded. In contrast, the UN method improves the BadRSRP of both the faulty cell and the neighboring cells, but it is not able to improve the $SINR_{50}$ of the faulty cell. This is an important limitation since the main effect of the considered fault (i.e., weak coverage fault) is the signal quality degradation. The proposed solution in this case is to combine the compensation method based on HOM

modifications with tilt modifications (UN+HOcomp) to compensate both the SINR degradation and the coverage holes. The combination consists of a first phase with tilt modifications and a second phase when the proposed algorithm is activated and the antenna tilt does not change. Results show that the latter method achieves an important improvement in both BadRSRP and $SINR_{50}$.

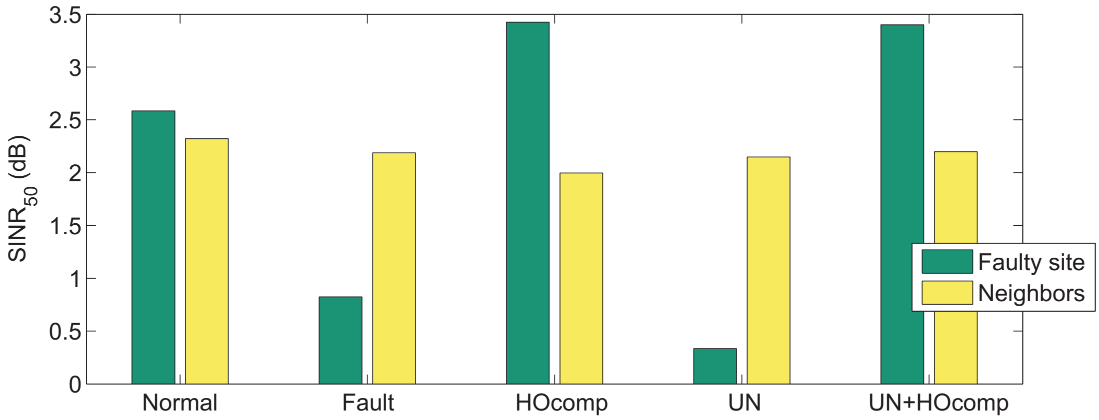

Figure 6.23: Results for cosited faulty site with coverage problem: $SINR_{50}$ (dB).

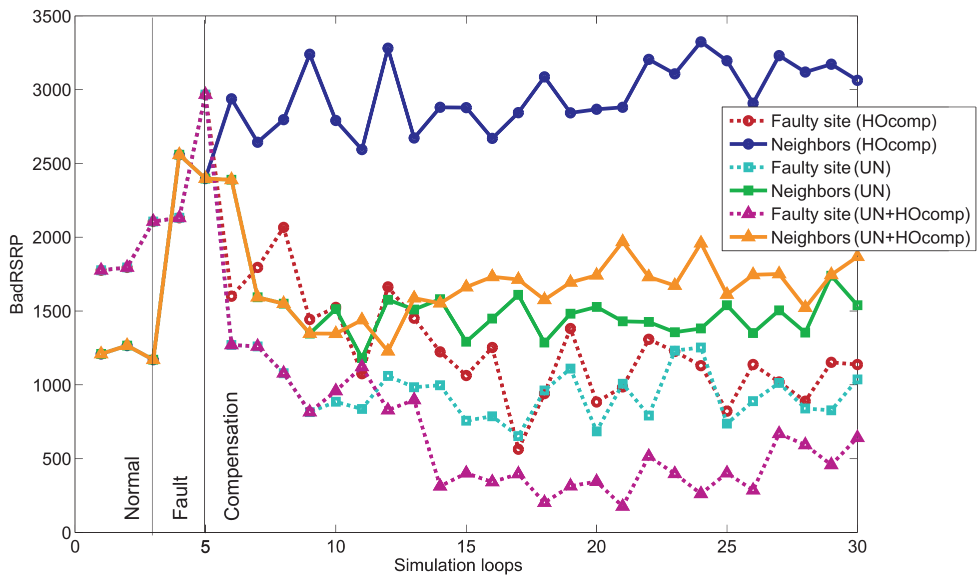

Figure 6.24: Results for cosited faulty site with coverage problem: BadRSRP.

The last test considers two faulty cells that are not cosited. The selected faulty cells are the original cell (i.e., cell 11) and one of its main neighboring cells (i.e., cell 3). The selected compensating neighbors for cell 3 are: 1, 2, 6, 10, 11 and 32. Cell 11 is not considered as compensating cell since it is also affected by the fault. The algorithm settings for cell 3 are the same as for cell 10 and as described before (i.e., Thr_3=1 and Thr_4=2).

Fig. 6.25 shows the obtained results. All figures present the obtained results for the two faulty cells and the neighboring cells. It can be seen that in the two cases the results are similar.

These results allow to conclude that the fact that more than one cell experiences the fault simultaneously is not an impediment to successfully compensate the problem. In this case the minimum values for the HOM are -5 dB for cell 3 and -7 dB for cell 11.

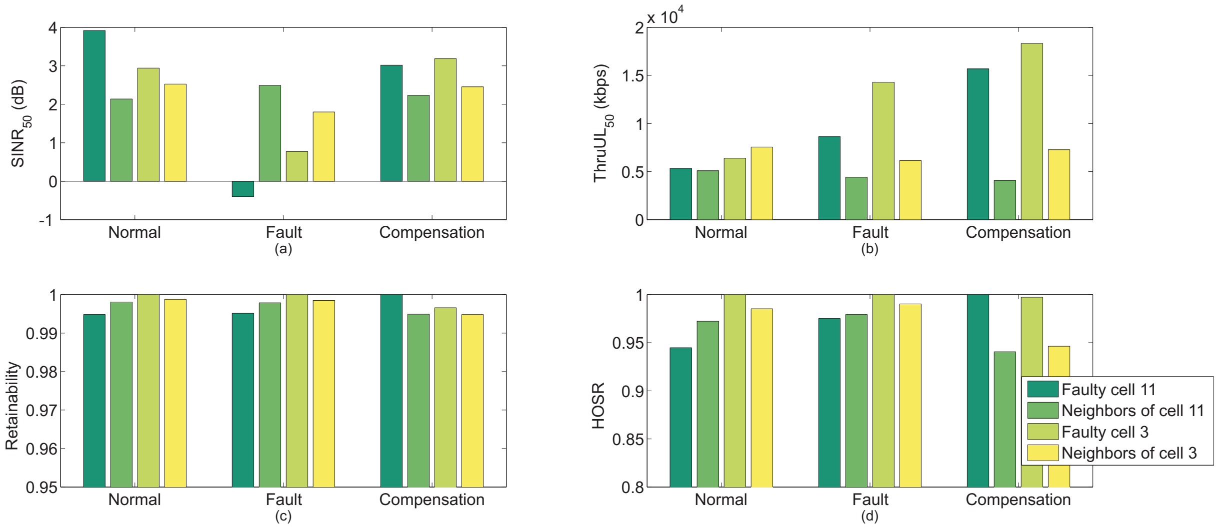

Figure 6.25: Results for non-cosited faulty cells: (a) $SINR_{50}$ (dB), (b) $ThrUL_{50}$ (kbps), (c) Retainability and (d) HOSR.

6.6 Conclusions

In this chapter, a CDC algorithm for a weak coverage fault has been presented.The proposed algorithm modifies HOMs in order to reduce the degradation caused by a weak coverage fault occurred in the network. The proposed method also includes a previous stage that performs an automatic selection of neighboring cells to carry out the compensation and an automatic configuration to adapt internal algorithm settings to different scenario conditions. The algorithm, which has been implemented by a FLC, computes the HOM increments (or decrements) based on the performance of the faulty cell and the neighboring cells. A set of simulations has been carried out to evaluate the proposed compensation algorithm under different conditions. These tests include different levels of degradation in the faulty cell, different user mobility conditions or multiple faulty cells. Results have shown that the proposed algorithm is able to improve the signal quality experienced by the users in the faulty cell. Such an improvement is achieved at the expense of a slight reduction of the signal quality in neighboring cells and a slight degradation of the HOSR, especially when the level of degradation is high.

In addition, a combination of the proposed algorithm with another technique based on tilt modifications has been presented. This approach is interesting when the weak coverage fault causes coverage holes.

Chapter 7

Conclusions

This chapter summarizes the main contributions of this thesis. In addition, some future lines of work are suggested. Finally, a list of publications related to this thesis is presented.

7.1 Contributions

This thesis is focused on two use cases defined by the 3GPP in the context of Self-Healing for mobile networks. Specifically, the work developed in this thesis includes new proposals for the detection and fault compensation functions. According to the structure of this report, the main contributions of this thesis can be organized in the following lines:

a) Simulation tool

A computationally-efficient tool for dynamic system-level LTE simulations has been developed in order to analyze the different algorithms proposed in this thesis. The definition, implementation and validation of this simulator have been part of this thesis. A physical layer abstraction is included to predict link-layer performance with a low computational cost. Thus, realistic OFDM channel realizations with multi-path fading propagation conditions have been generated. Additionally, the main RRM functions such as link adaptation, dynamic scheduling, admission control and mobility management are included in the simulator. The simulator is conceived for large simulated network time to evaluate the SON functions proposed in this work.

b) Cell Outage Detection

Most COD algorithms found in the literature are based on detecting cells in outage by monitoring KPIs or alarms from the cell in outage. Other works present COD algorithms that are based on neighboring cell measurements. The main drawback of the first approaches is that they can detect outages only when there are available KPIs from the cell in outage, but there are many situations when the outage affects a whole site and the eNB is also affected. The second group of solutions need user traces to perform the detection, but trace collection is normally disabled in live networks to reduce processor load in the eNB.

A novel COD algorithm has been proposed in this thesis. The proposed algorithm is based on the number of inHO measured on a per-cell basis by neighboring cells. Specifically, the proposed algorithm monitors situations where the number of inHO becomes zero as a potential symptom of cell outage. The main advantages of the algorithm are that: a) it is capable of detecting cell outages even if the base station is also affected, and b) it is based on performance counters that are available in the network management system. Due to the simplicity of the algorithm, it is possible to perform the detection immediately after collecting the KPIs.

c) Cell Outage Compensation

Most works related to COC in the literature assume that the main effect produced by the cell outage is a coverage hole. In densely populated area, where many sites are deployed, this is not typically the case. One of the main contributions of this thesis has been to overcome this limitation.

- **Analysis of cell outages**. One of the main contributions of this thesis is considering that each cell outage situation may produce different effects in the neighboring cells. For this reason, it is essential to analyze the degradation caused in the neighboring cells when a cell outage occurs. In this sense, the analysis of massive amount of data can provide several benefits together with new avenues and challenges for improving the COC by analyzing real data sets of cell outages. In this thesis, the analysis of data collected in neighboring cells has led to the following contributions:

  – First, the idea of addressing the problem of each neighbor of a cell in outage as an independent case, as opposed to the state-of-the-art approach of not considering the different effects of the outage on neighbors. The proposed approach is based on the fact that cell outages can impact on each neighboring cell in a different way. For instance, in some cases, a cell outage could lead to mobility issues in neighboring cells due to a lack of a dominant cell, whereas, in other cases, the cell outage may produce a coverage hole. The analysis of effects is made by measuring the correlation (dependence) between KPIs in order to extract valuable information from a vast amount of data. Depending on whether the dataset includes historical (offline) or real-time (online) information of cell outages, different methods have been proposed to estimate the impact of outages on neighboring cells. To illustrate this approach, an analysis of cell outages in a mature LTE network has been carried out by looking at degraded metrics in neighboring cells.

  - Second, the idea that estimating the amount of traffic that is potentially lost as a consequence of cell outages should be considered by COC policies. This is important, since lost traffic can result in a potential loss of market share and revenues for the service provider. A method to estimate the lost traffic based on computing the traffic absorbed by neighboring cells has been proposed.

- **Adaptive COC algorithms**. By taking advantage of the previous cell outage analysis, a new COC approach from the perspective of neighboring cells is discussed. Current COC solutions are typically focused on modifying a specific radio parameter (e.g., the antenna downtilt or the base station transmit power) in a predetermined number of neighboring cells to solve in most cases a problem of coverage hole. In this thesis, the shortcomings of this kind of solutions have been addressed and an improvement of the COC function has been presented. Such an improvement is achieved by adapting the COC function to each particular cell outage failure depending on the different effects that a cell outage may produce in the neighboring cells. Once a cell outage is detected, a detailed analysis of the effects produced in the neighboring cells is carried out. Based on the results of this analysis, it is possible to determine the set of cells that will take part in the compensation and the control parameter to be modified on a cell basis in order to adapt the compensation to the specific problem detected in each neighboring cell. Thus, the COC function is focused on mitigating the particular degradation caused by the cell outage.

  More specifically, three different COC fuzzy algorithms based on the modification of antenna tilt and HOM have been proposed. Antenna tilt modifications has been widely used for outage compensation in the literature. However, HO parameters have not previously been used with this purpose. Typically, the modification of HO parameters has been used for other SON functions, such as mobility robustness optimization or load balancing in case of congestion.

d) Cell Degradation Compensation

State-of-the-art compensation works aim to compensate a specific failure, namely the cell outage problem. In this thesis, the compensation of a network failure different to the cell outage is considered. Specifically, the analyzed degradation is a coverage deterioration in a cell due to a reduction of its transmission power in the downlink. The transmission power reduction may be caused by wiring problems or a wrong parameter configuration. In this situation, the faulty cell is still carrying traffic although its coverage area is reduced due to the fault. Thus, the faulty cell can be considered for the compensation process. This thesis has proposed to use the HOM as a new parameter for compensating cell degradation. In particular, the original contribution is related to two main aspects:

- First, this work has considered a weak coverage fault, which is a different problem as the cell outage problem commonly addressed in SON literature. When a cell is in outage, it cannot carry traffic. Therefore, the main effect caused by a cell outage is the total loss of service in the problematic area. In such a situation, it is not possible to consider the faulty cell as a part of the compensation algorithm. This thesis has proposed a compensation algorithm with the aim of mitigating the effects caused by a weak coverage fault considering modifications of the faulty cell parameters as part of the compensation method. Moreover, the degradation produced by the fault will be different to the one produced by a cell outage.

- Second, this work has proposed a compensation algorithm based on HOM modifications, including the faulty cell and its neighbors. The use of this parameter with a compensation objective is an important contribution of this work. The HOM has been extensively used with optimization purposes, but it has not been previously considered for fault compensation.

7.2 Future work

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

- One of the main research lines addressed in this thesis is the detection of failures in a network. In particular, this thesis is focused on the detection of the cell outage problem. A possible line of future work is the definition and implementation of cell detection algorithms that detect other kind of failures. Specifically, a cell detection algorithm to detect a weak coverage failure can be defined.

- The COC use case has also been considered in this thesis. In this case, the network failures considered are the cell outage and the weak coverage. However, there are many other failures that can occur and need compensation actions (e.g., missing neighbors, external interference, high traffic, etc.).

- The proposed method for cell outage analysis is based on the correlation of a set of KPIs. In this thesis, the most representative KPIs have been selected. However, depending on the kind of degradation, the most interesting KPIs may be different. In order to improve the analysis method, the set of considered KPIs can be extended. In addition, the selection of the most appropriate KPIs for each kind of degradation can be made automatically. The main drawback of this approach is that the complexity of the analysis increases. Recent development of Big Data and Data Mining techniques may help operators to cope with such a complexity.

- Considering the previous possible lines, the ultimate goal may be to define a complete Self-Healing framework that allows to detect a large amount of different failures in a live network, to analyze the degradation produced by the fault in both the faulty cell and the neighboring cells, so as to adapt the compensation algorithms to mitigate the negative effects caused by the fault as quickly as possible.

- A relevant issue in the field of SON is the coordination of use cases. In this context, the coordination between the proposed compensation algorithms, based on modifying HOMs and tilts, and optimization methods, such as mobility robustness optimization, load balancing or CCO algorithms, can be explored.

- Finally, this thesis is focused on the development of SON functionalities. These features allow to cope with the complexity of network operation and to reduce costs. These two issues are foreseen to be the biggest challenges in 5th Generation (5G). A possible line of future work is the extension of the proposed methods to 5G networks by adapting the algorithms to the specific characteristics of these new networks (e.g., considering small cells).

7.3 Publications and projects

The following subsections present the publications related to this thesis.

7.3.1 Journals

Publication arising from this thesis

[I] I. de-la-Bandera, R. Barco, P. Muñoz and I. Serrano, "Cell Outage Detection Based on Handover Statistics", *IEEE Communications Letters*, vol. 19, no. 7, pp. 1189-1192, July 2015.

[II] I. de-la-Bandera, R. Barco, P. Muñoz, A. Gómez-Andrades, and I. Serrano, "Fault Compensation Algorithm based on Handover Margins in LTE Networks", *EURASIP Journal on Wireless Communications and Networking*, (2016) 2016:246, October 2016.

[III] I. de-la-Bandera, P. Muñoz, I. Serrano and R. Barco, "Improving Cell Outage Management Through Data Analysis", *IEEE Wireless Communications*, vol.PP, no.99, pp.2-8, February 2017.

[IV] I. de-la-Bandera, P. Muñoz, I. Serrano and R. Barco, "Adaptive Cell Outage Compensation in Self-Organizing Networks", *IEEE Transactions on Vehicular Technology*, Under review, 2016.

[V] P. Muñoz, I. de-la-Bandera, F. Ruiz, S. Luna-Ramírez, R. Barco, M. Toril, P. Lázaro and J. Rodríguez, "Computationally-Efficient Design of a Dynamic System-Level LTE Simulator", *International Journal of Electronics and Telecommunications*, 2011.

Publication related to this thesis

[VI] P. Muñoz, R. Barco, I. de-la-Bandera, E. J. Khatib, A. Gómez-Andrades and I. Serrano, "Root Cause Analysis based on Temporal Analysis of Metrics toward Self-Organizing 5G Networks", *IEEE Transactions on Vehicular Technology*, Accepted, 2016.

[VII] A. Gómez-Andrades, P. Muñoz, E. J. Khatib, I. de-la-Bandera, I. Serrano and R. Barco, "Methodology for the Design and Evaluation of Self-Healing LTE Networks", *IEEE Transactions on Vehicular Technology*, vol. 65, no. 8, pp. 6468-6486, Aug. 2016.

[VIII] E. J. Khatib, R. Barco, P.Muñoz, I. de-la-Bandera and I. Serrano, "Self-healing in mobile networks with big data", *IEEE Communications Magazine*, vol. 54, no. 1, pp. 114-120, January 2016.

[IX] R. Acedo-Hernández, M. Toril, S. Luna-Ramírez, I. de-la-Bandera and N. Faour, "Analysis of the impact of PCI planning on downlink throughput performance in LTE", *Computer Networks*, 76 - 1, pp. 42-54, 2015.

[X] P. Muñoz, R. Barco and I. de-la-Bandera, "Load Balancing and Handover Joint Optimization in LTE Networks using Fuzzy Logic and Reinforcement Learning", *Computer Networks*, vol. 76, pp. 112-125, 2015.

[XI] P. Muñoz, R. Barco and I. de-la-Bandera, "On the Potential of Handover Parameter Optimization for Self-Organizing Networks", *IEEE Transactions on Vehicular Technology*, vol. 62, no. 5, pp. 1895-1905, Jun 2013.

[XII] P. Muñoz, R. Barco and I. de-la-Bandera, "Optimization of Load Balancing using Fuzzy Q-Learning for Next Generation Wireless Networks", *Expert Systems with Applications*, vol. 40, no. 4, pp. 984-994, March 2013.

[XIII] P. Muñoz, R. Barco, J. M. Ruiz-Avilés, I. de-la-Bandera and A. Aguilar, "Fuzzy Rule-based Reinforcement Learning for Load Balancing Techniques in Enterprise LTE Femtocells", *IEEE Transactions on Vehicular Technology*, vol. 62, no. 5, pp. 1962-1973, Jun 2013.

[XIV] J. M. Ruiz-Avilés, S. Luna-Ramírez, M. Toril, F. Ruiz, I. de-la-Bandera, P. Muñoz, R. Barco, P. Lázaro and V. Buenestado, "Design of a Computationally Efficient Dynamic System-Level Simulator for Enterprise LTE Femtocell Scenarios", *Journal of Electrical and Computer Engineering*, 2012.

7.3.2 Patents

Patents arising from this thesis

[XV] I. de-la-Bandera, R. Barco, P. Muñoz and I. Serrano, "First network node, method therein, computer program and computer-redeable medium comprising the computer program for detecting outage of a radio cell", WO 2016068761 A1, 2016.

Patents related to this thesis

[XVI] P. Muñoz, R. Barco, I. Serrano and A. Gómez-Andrades, "First network node, method therein, computer program and computer-readable medium comprising the computer program for determining whether a performance of a cell is degraded or not", WO/2016/169616, 2016.

[XVII] V. Buenestado, M. Toril, J. M. Ruiz-Avilés, I. de-la-Bandera and M. A. Regueira, "A new cell overshooting indicator for optimizing remote electrical tilt", WO2015002676 A1, 2015.

7.3.3 Conferences and Workshops

Conferences arising from this thesis

[XVIII] I. de-la-Bandera, R. Barco, P. Muñoz and I. Serrano, "A Novel Cell Outage Detection Method for Self-Organizing Networks", *13th MC & Scientific Meeting COST IC1004*, Valencia (Spain) 2015.

[XIX] I. de-la-Bandera, R. Barco, A. Gómez-Andrades, P. Muñoz and I. Serrano, "Compensación de Celdas Degradadas en Redes LTE", *XXIV Simposium nacional de la Unión Científica Internacional de Radio, Valencia (Spain)*, 2014.

Conferences related to this thesis

[XX] A. Gómez-Andrades, P. Muñoz, E. J. Khatib, I. de-la-Bandera, I. Serrano and R. Barco, "Simulador de fallos en una red LTE para sistemas de diagnosis", *XXIV Simposium nacional de la Unión Científica Internacional de Radio, Valencia (Spain)*, 2014.

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[XXII] P. Oliver-Balsalobre, M. Toril, I. de-la-Bandera, S. Luna-Ramírez and J. M. Ruiz-Avilés, "Simulador Dinámico Multi-Servicio para Análisis de la Calidad de Experiencia en Redes LTE", *XXIV Simposium nacional de la Unión Científica Internacional de Radio, Valencia (Spain)*, 2014.

[XXIII] J. A. Fernández-Segovia, A. J. García-Pedrajas, I. de-la-Bandera, M. Toril and S. Luna-Ramírez, "Simulador estático de nivel de sistema del canal ascendente de datos en redes LTE", *XXIV Simposium nacional de la Unión Científica Internacional de Radio, Valencia (Spain)*, 2014 .

[XXIV] R. Acedo-Hernández, M. Toril, S. Luna-Ramírez and I. de-la-Bandera, "Análisis de la planificación de señales de referencia en LTE con tráfico no uniforme", *XXVIII Simposium* *nacional de la Unión Científica Internacional de Radio, Santiago de Compostela (Spain)*, 2013.

[XXV] J. M. Ruiz-Avilés, I. de-la-Bandera, V. Buenestado and M. Toril, "Construcción de Contadores Sintéticos mediante Procesado de Eventos Complejo en redes LTE", *XXVIII Simposium nacional de la Unión Científica Internacional de Radio, Santiago de Compostela (Spain)*, 2013.

[XXVI] R. Acedo-Hernández, M. Toril, S. Luna-Ramírez and I. de-la-Bandera, "Analysis of the impact of PCI planning on throughput performance in LTE", *6th Management Committe And Scientific Meeting, Action Cost Ic1004*, Málaga (Spain), 2013.

[XXVII] P. Muñoz, I. de-la-Bandera, R. Barco, M. Toril, S. Luna-Ramírez and J. M. Ruiz-Avilés, "Sensitivity Analysis and Self-Optimization of LTE Intra-Frequency Handover", *6th Management Committe And Scientific Meeting, Action Cost Ic1004*, Málaga (Spain), 2013.

[XXVIII] J. Rodríguez-Membrive, I. de-la-Bandera, P. Muñoz and R. Barco, "Load Balancing in a Realistic Urban Scenario for LTE Networks", *IEEE 73RD Vehicular Technology Conference, VTC*, Budapest (Hungary), 2011.

[XXIX] P. Muñoz, R. Barco, I. de-la-Bandera, M. Toril and S. Luna-Ramírez, "Optimization of a Fuzzy Logic Controller for Handover-Based Load Balancing", *IEEE 73RD Vehicular Technology Conference, VTC*, Budapest (Hungary), 2011.

[XXX] I. de-la-Bandera, P. Muñoz, R. Barco, M. Toril and S. Luna-Ramírez, "Auto-Ajuste del Margen de Handover en Redes LTE,", *XXVI Simposium Nacional de la Unión Científica Internacional de Radio*, Leganés (Spain), 2011

[XXXI] P. Muñoz, I. de-la-Bandera, R. Barco, M. Toril and S. Luna-Ramírez, "Optimización del Balance de Carga en Redes LTE Mediante el Algoritmo de Q-Learning Difuso,", *XXVI Simposium Nacional de la Unión Científica Internacional de Radio*, Leganés (Spain), 2011.

[XXXII] J. Rodríguez-Membrive, I. de-la-Bandera, P. Muñoz and R. Barco, "Balance de carga en escenario urbano mediante controlador difuso para redes LTE", *XXVI Simposium Nacional de la Unión Científica Internacional de Radio*, Leganés (Spain), 2011.

[XXXIII] J. M. Ruiz-Avilés, S. Luna-Ramírez, M. Toril, F. Ruiz-Vega and I. de-la-Bandera, "Simulación Eficiente de Red de Femtoceldas LTE en Entornos de Oficina", *XXVI Simposium Nacional de la Unión Científica Internacional de Radio*, Leganés (Spain), 2011.

[XXXIV] J. M. Ruiz-Avilés, S. Luna-Ramírez, M. Toril, F. Ruiz-Vega, I. de-la-Bandera and P. Muñoz, "Analysis of Load Sharing Techniques in Enterprise LTE Femtocells", *Wireless Advanced (WIAD)*, London(UK), 2011.

[XXXV] I. de-la-Bandera, S. Luna-Ramírez, R. Barco, , M. Toril, F. Ruiz.Vega and M. Fernández-Navarro, "Controlador Difuso para Auto-Ajuste de Parámetros en Entorno de Red Móvil Heterogénea,", *XXV Simposium Nacional de la Unión Científica Internacional de Radio*, Bilbao (Spain), 2010.

[XXXVI] P. Muñoz, I. de-la-Bandera, R. Barco, F. Ruiz-Vega, M. Toril and S. Luna-Ramírez, "Diseño del Nivel de Enlace para un Simulador LTE", *XXV Simposium Nacional de la Unión Científica Internacional de Radio*, Bilbao (Spain), 2010.

[XXXVII] I. de-la-Bandera, S. Luna-Ramírez, R. Barco, M. Toril, F. Ruiz.Vega and M. Fernández-Navarro, "Inter-System Cell Reselection Parameter Auto-Tuning in a Joint-RRM Scenario", *IEEE Fifth International Conference on Broadband and Biomedical Communications (IB2COM)*, Málaga (Spain), 2010.

[XXXVIII] P. Muñoz, I. de-la-Bandera, R. Barco, F. Ruiz-Vega, M. Toril and S. Luna-Ramírez, "Estimation of Link-Layer Quality Parameters in a System-Level LTE Simulator", *IEEE Fifth International Conference on Broadband and Biomedical Communications (IB2COM)*, Málaga (Spain), 2010.

7.3.4 Book chapters

[XXXIX] P. Muñoz, I. de-la-Bandera, F. Ruiz-Vega, S. Luna-Ramírez, J. Rodríguez-Membrive, R. Barco, M. Toril, P. Lázaro and M. Fernández-Navarro, "Developing a Computationally-Efficient Dynamic System-Level LTE Simulator", *4G Wireless Communication Networks: Design, Planning and Applications, River Publishers*, 2013

7.3.5 Related projects

This thesis was partially funded by the following projects:

- P08-TIC-4052 grant from the Junta de Andalucía.
- 8.06/5.59.3721, contract with Optimi-Ericsson, with support from the Junta de Andalucía (Agencia IDEA, Consejería de Ciencia, Innovación y Empresa) and ERFD.
- 8.06/5.59.3722, contract with Optimi-Ericsson, with support from the Junta de Andalucía (Agencia IDEA, Consejería de Ciencia, Innovación y Empresa) and ERFD.
- P12-TIC-2905 grant from the Junta de Andalucía.

Appendix A

Summary (Spanish)

A.1 Introducción

A.1.1 Antecedentes y justificación

Durante las últimas décadas, la industria de las comunicaciones móviles ha experimentado un crecimiento importante que ha llevado a una constante evolución de las tecnologías relacionadas. Al mismo tiempo, el número de usuarios que demandan servicios móviles ha crecido de manera exponencial y el 95% de la población vive en un área con cobertura de alguna red móvil [1]. Como resultado, los terminales móviles (p. ej., *smartphones*) se han convertido en un elemento esencial para la mayoría de las personas, que los utilizan en los distintos ámbitos de la vida diaria. No solo constituyen un instrumento básico en muchos trabajos, sino que además ocupan una parte importante del tiempo de ocio. Esto ha provocado un aumento de la complejidad y variedad de los servicios demandados.

Para hacer frente al gran número de usuarios y la complejidad de los actuales servicios de comunicaciones móviles, las tecnologías desarrolladas han tenido que evolucionar rápidamente. Las primeras redes digitales (*Global System for Mobile communications*, GSM) proporcionaban un servicio de voz de alta calidad, permitiendo la primera gran expansión de las redes móviles. Sin embargo, los usuarios pronto empezaron a demandar otros tipos de servicios y estas redes resultaban insuficientes para responder a la creciente demanda. En aquel momento, surgió la tercera generación (3G) de redes móviles (*Universal Mobile Telecommunications System*, UMTS). Este estándar, desarrollado por el grupo *3rd Generation Partnership Project* (3GPP), ofrecía servicios de datos además del servicio de voz. Las redes 3G continuaron evolucionando con el objetivo de mejorar el rendimiento y ofrecer servicios más complejos. Actualmente, un nuevo estándar (*Long Term Evolution*, LTE) se está desplegando para hacer frente a la enorme demanda de servicios. Los principales beneficios de LTE se pueden resumir en una mejora del rendimiento del sistema, mayores tasas de transmisión y eficiencia espectral, reducción de latencia y consumo de potencia, mejoras en el uso del espectro y simplificación de la arquitectura de la red [2].

En los escenarios actuales, los operadores de red tiene dos objetivos principales: satisfacer la gran cantidad de tráfico demandado y mantener los gastos de capital y operación en valores mínimos. La manera más efectiva de alcanzar este objetivo es mediante la automatización de las tareas de gestión de la red. Este es el principal propósito de las redes Auto-Organizadas (*Self-Organizing Networks*, SONs) [3]. El concepto SON se publicó por primera vez en 2008 por la alianza *Next Generation Mobile Networks* (NGMN) [4, 5]. Después, el grupo 3GPP también incluyó el concepto SON como un elemento clave en su nuevo estándar de comunicaciones móviles, LTE. Además, la complejidad y el coste de las futuras redes de quinta generación (5G) será aún mayor, por lo que la funcionalidades SON resultarán imprescindibles [6, 7]. El grupo 3GPP define tres categorías de funciones SON [3]: Auto-Configuración, Auto-Optimización y Auto-Curación. Las funciones de Auto-Configuración [8] buscan automatizar la definición de los parámetros de configuración de los elementos de red en la fase de planificación o durante el despliegue de un nuevo equipo. El objetivo de las funciones de Auto-Optimización [8] es el ajuste automático de los parámetros de red para adaptarse a las diferentes condiciones de cada escenario. Por último, las funciones de Auto-Curación [9, 10] se relacionan con los fallos que pueden ocurrir en la red y empeorar su rendimiento. En concreto, entre las funciones de Auto-Curación (Fig. 1.1) se encuentran la recogida de información sobre el rendimiento de la red, la detección y diagnosis de fallos y la compensación o recuperación para reducir o solventar el problema.

Además de los operadores de red, la comunidad científica también ha mostrado un creciente interés en las funciones SON. Así, en los últimos años, muchos proyectos de investigación internacionales se han centrado en el desarrollo de métodos para la optimización y el mantenimiento de redes móviles. Algunos de estos proyectos son CELTIC Gandalf [11], E3 [12], SOCRATES [13], SELF-NET [14], UniverSelf [15], SEMAFOUR [16] y COMMUNE [17]. La mayoría de estos proyectos se centran en las funciones de Auto-Configuración y Auto-Optimización, mientras que las funciones de Auto-Curación han recibido menos atención. Además, no todas las funciones de Auto-Curación han sido tratadas con la misma profundidad. Así, se pueden encontrar muchos algoritmos relacionados con la tarea de detección de fallos [18, 19, 20, 21, 22, 23, 24, 25, 26]. En muchos casos, la detección se lleva a cabo analizando el comportamiento de la red y comparándolo con el funcionamiento normal de la misma. Uno de los posibles fallos que puede ocurrir en una red móvil es el fallo de celda caída. Una celda se considera caída cuando no puede servir tráfico debido a un fallo. En la literatura, se pueden encontrar diferentes trabajos relacionados con la función de detección de celda caída (*Cell Outage Detection*, COD) [27, 28, 29, 30, 31, 32]. La mayoría de estos trabajos se basan en el análisis del rendimiento de la celda problemática y las celdas vecinas. La práctica demuestra que, con esta metodología, solo se pueden detectar los casos más graves, quedando otros muchos sin detectar. Algunos métodos [30] son capaces de detectar la mayoría de los casos de celda caída pero a cambio de una elevada complejidad.

Además del caso de uso de COD, el 3GPP define otros casos de uso de Auto-Curación, como el caso de uso de compensación de celda caída (*Cell Outage Compensation*, COC) [9].

La función de COC pretende reducir la degradación producida en una celda debida a un fallo hasta que éste se solventa. La compensación puede realizarse modificando diferentes parámetros de configuración de la red. Estos parámetros suelen afectar a las celdas vecinas de la celda caída. Todas las modificaciones que se lleven a cabo durante un proceso de compensación deben revertirse una vez que el fallo se ha solucionado. En la bibliografía, se han propuesto diversos algoritmos de COC [33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45]. En estos trabajos, los autores presentan diferentes algoritmos basados en la modificación de uno o más parámetros de red mediante diferentes técnicas (p.ej., lógica difusa, aprendizaje por refuerzo). En todos ellos, el principal objetivo es reducir la degradación producida por un fallo de celda caída. Sin embargo, estos trabajos presentan dos limitaciones importantes. Por un lado, todos los trabajos anteriores asumen que el principal efecto producido por un fallo de celda caída es un hueco de cobertura. Así, el principal objetivo de estos algoritmos es cubrir el área de la celda caída incrementando el área de cobertura de las celdas vecinas. Sin embargo, un problema de celda caída puede producir diferentes efectos dependiendo del tipo de escenario y las condiciones de la red. Por ejemplo, en una red con un alto grado de solapamiento entre celdas, una celda caída puede no llegar a producir un hueco de cobertura. En estas condiciones, una celda caída puede producir problemas de movilidad entre celdas vecinas o congestión en el caso de que la cantidad de tráfico absorbido por las vecinas sea suficientemente alto. Además, en estos casos, un único problema de celda caída puede tener diferentes efectos en cada una de las celdas vecinas. Por lo tanto, cuando un fallo de celda caída no produce un problema de hueco de cobertura y la degradación observada en las vecinas no está relacionada con la cobertura, los métodos de COC propuestos hasta la fecha podrían no ser efectivos.

Por otro lado, en todos estos trabajos, los diferentes algoritmos se aplican siempre sobre un mismo fallo, el caso de celda caída. Sin embargo, existen otros muchos fallos que pueden afectar al rendimiento de la red [46]. Estos otros fallos (p.ej., *overshooting*, cobertura débil, etc.) pueden causar una importante degradación en la red, haciendo necesario un proceso de compensación hasta que el fallo sea reparado. En esos casos, la celda problemática puede seguir sirviendo tráfico y, por tanto, puede considerarse para formar parte del proceso de compensación.

Considerando las limitaciones de los trabajos citados anteriormente, esta tesis se centra en la mejora de las funciones de detección y compensación del fallo de celda caída así como la extensión de la función de compensación a otros fallos.

A.1.2 Objetivos

El principal objetivo de esta tesis es el diseño y desarrollo de algoritmos para la detección y compensación de fallos en una red móvil. Con este propósito, esta tesis aborda dos fases importantes del proceso de Auto-Curación, como son la detección del problema y la compensación del mismo.

La Fig. 1.2 presenta las distintas fases de un proceso típico de Auto-Curación. Cuando ocurre un fallo en una red, la primera fase es la detección y diagnosis del mismo. Una vez que el fallo está identificado, la función de compensación intenta mitigar la degradación producida por el fallo mientras éste se resuelve. Una vez que esto ocurre, los cambios hechos por el algoritmo de compensación deben revertirse. Esta tesis abarca las fases de detección y compensación. La Fig. 1.2 también presenta los objetivos de la tesis (recuadros amarillos).

Para alcanzar el principal objetivo de la tesis, se han abordado varias líneas de investigación:

Obj.1 *Diseño de un algoritmo de COD.* El primer objetivo es diseñar un algoritmo de COD que mejore la tasa de detección correcta de trabajos anteriores, sin aumentar la complejidad del mismo.

Obj.2 *Diseño de una metodología novedosa de COC.* Una vez que se detecta el fallo de celda caída, el segundo objetivo es proponer una nueva metodología de COC. Esta nueva metodología se basa en la idea de considerar cada celda vecina de la celda caída como un caso independiente, a diferencia de trabajos anteriores, que no consideran la posibilidad de que un mismo fallo de celda caída pueda provocar diferentes efectos en las vecinas. La principal idea es tener en cuenta que un fallo de celda caída puede afectar de distinta manera a las distintas celdas vecinas. Por ejemplo, en algunos casos, una celda caída puede provocar problemas de movilidad en las celdas vecinas debido a una falta de celda dominante, mientras que en otros casos, la celda caída puede producir un hueco de cobertura. Este método consiste en dos fases:

> **Obj.2.1** *Análisis de la degradación causada por la celda caída.* El análisis debe realizarse midiendo la relación entre los distintos indicadores de rendimiento (*Key Performance Indicator*, KPI) con el objetivo de extraer información útil de una gran cantidad de datos disponibles en el sistema de gestión de red. Además, debe realizarse una estimación de la cantidad de tráfico que podría perderse a consecuencia de la celda caída. Dicha estima es importante, ya que una pérdida de tráfico puede resultar en una potencial pérdida de mercado y de ingresos para el proveedor de servicios.
>
> **Obj.2.2** *Diseño de algoritmos de COC adaptativos.* A partir del análisis previo, es posible seleccionar el conjunto de celdas que deberán tomar parte del proceso de compensación y los parámetros de control que deben modificarse para cada celda. Así, la función COC se adaptará a la degradación específica detectada en cada celda vecina.

Obj.3 *Diseño de un novedoso algoritmo de compensación de celda degradada.* El tercer objetivo es diseñar un algoritmo de compensación para un fallo diferente al de celda caída. Aunque el estudio de la función de COC está muy extendido, todos los trabajos previos consideran el fallo de celda caída en sus estudios. Por el contrario, en esta tesis, se ha considerado un fallo diferente. En concreto, la degradación considerada consiste en un deterioro de la cobertura de una celda debido a una reducción de su potencia de transmisión en el enlace descendente. Este problema puede estar causado por problemas en el cableado o una mala configuración de los parámetros de un equipo. En esta situación, la celda problemática sigue sirviendo tráfico, aunque la zona de cobertura se ve reducida debido al fallo. Así, la propia celda problemática puede considerarse para formar parte del proceso de compensación.

Obj.4 *Desarrollo de una herramienta de simulación.* Por último, con el objetivo de evaluar los algoritmos anteriores, se ha implementado un simulador dinámico de nivel de sistema de LTE como parte de esta tesis.

A.2 Herramienta de simulación

En el capítulo 3 se presenta un simulador de nivel de sistema LTE dinámico computacionalmente eficiente. El simulador incluye las principales características de la red de acceso radio, así como los principales algoritmos de gestión de recursos radio para la mejora de la eficiencia espectral. En concreto, el simulador incluye una abstracción de la capa física que predice el rendimiento a nivel de enlace. Para ello, se ha implementado un modelo de canal OFDM (*Orthogonal Frequency Division Multiple*) en el simulador para caracterizar la variación del enlace en tiempo y frecuencia para cada usuario. Esto permite obtener indicadores a nivel físico y de enlace para analizar la calidad de conexión de los usuarios móviles. Estos indicadores se utilizan como entrada de las funciones de gestión de recursos radio.

En cuanto a la capa de enlace, el simulador incluye dos de las principales funciones para la mejora de la capacidad de la red: adaptación del enlace y planificador dinámico de recursos. A nivel de red el simulador incluye las principales funciones de gestión de recursos radio como control de admisión y gestión de movilidad.

El objetivo principal del desarrollo de esta herramienta es la evaluación de los algoritmos SON. Por esta razón, el simulador se ha implementado para tener un bajo coste computacional. Una simulación consiste en una serie de iteraciones para evaluar la modificación de parámetros de red llevadas a cabo por los algoritmos SON (por ejemplo, por un algoritmo de compensación de celda caída).

Por último, el capítulo describe una serie de experimentos destinados a analizar el comportamiento de tres algoritmos concretos: proceso de traspaso, algoritmo de control de congestión y algoritmo de planificación dinámica de recursos.

A.3 Detección de celda caída

El capítulo 4 presenta un algoritmo de COD basado en estadísticas de traspaso entrantes. Estos indicadores se encuentran disponibles en el sistema de gestión de red. El algoritmo propuesto es capaz de detectar celdas caídas incluso cuando la estación base está afectada ya que se basa en medidas realizadas por las celdas vecinas. En estos casos, no se dispone de indicadores de rendimiento de la celda problemática. En concreto, el algoritmo propuesto detecta los casos en los que el número de traspasos entrantes a una celda pasa a ser cero como síntoma de un posible fallo de celda caída. El capítulo presenta los resultados obtenidos en un conjunto de simulaciones y pruebas en una red real. Los resultados muestran que, a diferencia de los métodos descritos hasta la fecha, el algoritmo propuesto permite detectar la mayoría de los casos de celda caída en una red real. La principal limitación del algoritmo es que no todos los fallos que afectan a celdas con muy poco tráfico pueden detectarse. Sin embargo, estas situaciones afectarían a un grupo reducido de usuarios y, por tanto, tendrían un bajo impacto con respecto al rendimiento global de la red.

A.4 Compensación de celda caída

En el capítulo 5 se describe una nueva metodología de COC. El esquema de COC propuesto presenta una importante mejora de la función de COC que se obtiene al adaptar diferentes estrategias de COC a distintas situaciones de celda caída. La adaptación consiste en seleccionar de manera automática las celdas que llevarán a cabo la compensación, los parámetros de configuración modificados y la magnitud de la acción de compensación.

Como parte de esta nueva metodología de COC, se presenta un estudio de la degradación producida en celdas vecinas por fallos de celda caída en una red real. En concreto, se proponen tres métodos de análisis. Un primer método *offline* analiza la degradación producida por una celda caída en las celdas vecinas mediante la correlación de KPIs utilizando datos históricos de red relativos a este fallo. Los otros dos métodos son métodos *online* que se ejecutan inmediatamente después de detectar el fallo de celda caída. Estos dos métodos *online* se diferencian entre sí por el modo en que se determina si hay degradación en los distintos KPIs. Uno de ellos está basado en correlaciones y el otro en el método de detección de delta. En ambos casos, se puede determinar el tipo de degradación presente en cada una de las celdas vecinas de forma que se pueda adaptar eficazmente el algoritmo de compensación. Además, se presenta un método para estimar la cantidad de tráfico perdida a causa de la celda caída. Los resultados muestran que un fallo de celda caída puede producir diferentes tipos de degradación en las celdas vecinas que deben ser compensados de diferente manera.

En este capítulo también se propone un método de COC adaptativo que incluye varios algoritmos de COC. Una vez que el análisis previo ha determinado el conjunto de celdas afectadas y el tipo de degradación producido por la celda caída, un algoritmo de COC diferente se aplica a cada celda vecina. En concreto, en este trabajo se consideran tres situaciones de celda caída diferentes: una en la que se produce un hueco de cobertura, otra en la que se produce un problema de congestión y una última en la que la degradación producida está relacionada con un problema de movilidad. Los diferentes algoritmos de COC propuestos intentan mitigar la degradación mediante modificaciones del ángulo de inclinación de antena, el margen de traspaso o la histéresis de traspaso. En primer lugar, se ha llevado a cabo un estudio de sensibilidad para mostrar que diferentes tipos de situaciones de celda caída deben ser compensados modificando diferentes parámetros de control. Los resultados muestran que, para cada situación de celda caída, solo una de las estrategias de COC consigue una compensación exitosa. Basado en esta conclusión, tres algoritmos de COC implementados mediante controladores de lógica difusa se han aplicado a diferentes casos de celda caída. En todos los casos, el algoritmo de COC busca compensar la degradación producida por el fallo de celda caída sin afectar al resto de celdas del escenario. Por último, se presenta una última prueba considerando un escenario más realista en el que una misma celda caída produce diferentes tipos de degradación en diferentes vecinas al mismo tiempo. Los resultados muestran que el método de COC propuesto compensa con éxito esta situación.

A.5 Compensación de celda degradada

En el capítulo 6 se describe un algoritmo nuevo de compensación de celda degradada basado en modificaciones del margen de traspaso. A diferencia del capítulo anterior, el fallo considerado en este caso es un fallo de cobertura débil debido a una reducción de la potencia de transmisión de la estación base. En esta situación, la celda problemática se mantiene activa durante la compensación a pesar del fallo. El algoritmo propuesto incluye una fase previa que determina de manera automática el conjunto de celdas vecinas que llevará a cabo la compensación y la configuración automática del algoritmo para adaptarlo a las diferentes condiciones del escenario. El algoritmo, implementado a partir de un controlador de lógica difusa, calcula los incrementos (o decrementos) que hay que aplicar al margen de traspaso a partir del rendimiento de la celda problemática y las celdas vecinas. Se han llevado a cabo un conjunto de simulaciones para evaluar el algoritmo propuesto en distintas situaciones. Estas pruebas incluyen diferentes niveles de degradación en la celda problemática, diferentes condiciones de movilidad o múltiples celdas con fallo simultáneamente. También se han realizado varias simulaciones con distintas configuraciones del algoritmo. Los resultados muestran que el algoritmo propuesto mejora la calidad de señal experimentada por los usuarios de la celda problemática. Esta mejora se consigue a cambio de una pequeña reducción de la calidad de señal en las celdas vecinas y una leve degradación de la tasa de traspasos exitosos, especialmente cuando el nivel de degradación es alto.

Además, en el capítulo también se presenta una combinación del algoritmo propuesto con otra técnica basada en modificaciones del ángulo de inclinación de antena. Este método resulta interesante cuando el fallo de cobertura débil produce huecos de cobertura.

A.6 Conclusiones

El capítulo 7 resume las principales contribuciones de la tesis y las posibles líneas futuras. Además incluye una lista de las publicaciones relacionadas.

A.6.1 Contribuciones

Esta tesis se centra en dos casos de uso definidos por el 3GPP dentro del contexto de Auto-Curación en redes móviles. En concreto, el trabajo desarrollado en esta tesis incluye nuevos métodos para la detección de celdas caídas y la compensación de fallos. Siguiendo la estructura de este documento, las principales contribuciones de esta tesis se pueden organizar en las siguientes líneas:

a) Herramienta de simulación

Se ha desarrollado una herramienta computacionalmente eficiente para realizar simulaciones dinámicas de una red LTE de nivel de sistema para analizar los diferentes algoritmos propuestos en esta tesis. La definición, implementación y validación han formado parte de esta tesis.

b) Detección de celda caída

La mayoría de los algoritmos de COD que se encuentran en la literatura se basan en detectar celdas caídas a partir de los KPIs o alarmas de la propia celda caída. Otros trabajos presentan algoritmos de COD basados en medidas realizadas en las celdas vecinas. El principal inconveniente que presentan los primeros es que solo son capaces de detectar los casos de celdas caídas en los que hay KPIs disponibles de la propia celda problemática. Sin embargo, se pueden dar otros muchos casos de celdas caídas que afecten a la estación base y en los que no se dispongan de KPIs de la celdas problemáticas. El segundo grupo de soluciones necesitan trazas de usuarios para llevar a cabo la detección pero la recolección de esta información está normalmente desactivada en redes reales para reducir la carga del procesador de la estación base.

En esta tesis se propone un algoritmo nuevo de COD. El algoritmo propuesto se basa en el número de traspasos entrantes por celda medido a partir de las estadísticas de las celdas vecinas. En concreto, el método presentado monitoriza situaciones en las que el número de traspasos entrantes pasa a ser cero como síntoma de un posible caso de celda caída. Las principales ventajas de este método son: a) que es capaz de detectar celdas caídas incluso cuando la estación base se ha visto afectada, y b) está basado en contadores de rendimiento que están disponibles en el sistema de gestión de red. Debido a la simplicidad del algoritmo, es posible llevar a cabo una detección inmediatamente después de acceder a los KPIs.

c) Compensación de celda caída

La mayoría de los trabajos de COC encontrados en la literatura asumen que el principal efecto que produce una celda caída es un hueco de cobertura. En zonas de población densa, donde suele haber muchas celdas desplegadas, este no suele ser el efecto típico observado. Una de las principales contribuciones de esta tesis da respuesta a esta limitación.

- **Análisis de celdas caídas**. Una de las principales contribuciones de esta tesis es considerar que cada problema de celda caída puede producir diferentes efectos en las celdas vecinas. Por esta razón, es esencial analizar la degradación causada en las celdas vecinas cuando se da un fallo de celda caída. En este sentido, el análisis de una gran cantidad de datos reales relacionados con fallos de celdas caídas puede aportar importantes beneficios y mejoras en las técnicas de compensación del fallo. En esta tesis, el análisis de datos de celdas vecinas a celdas caídas ha llevado a las siguientes contribuciones:

– En primer lugar, la idea de considerar las celdas vecinas como independientes en un caso de celda caída, al contrario que los trabajos del estado del arte. El método propuesto se basa en el hecho de que un mismo caso de celda caída puede afectar de manera diferente a distintas celdas vecinas al mismo tiempo. Por ejemplo, en algunos casos, un problema de celda caída puede llevar a problemas de movilidad o congestión mientras que, en otros casos, se pueden producir huecos de cobertura. El análisis de los efectos de la celda caída se lleva a cabo midiendo la correlación (dependencia) entre los KPIs con el objetivo de extraer información útil de una gran cantidad de datos. En esta tesis se proponen diferentes métodos para estimar el impacto de los casos de celdas caídas dependiendo de si los datos contienen información histórica (*offline*) o de tiempo real (*online*). Para evaluar este método se ha realizado un análisis utilizando datos de una red LTE desplegada y actualmente en uso.

– En segundo lugar, la idea de que las políticas de COC deben considerar la estimación de la cantidad de tráfico que puede perderse debido al fallo de celda caída. Esto es importante ya que una pérdida de tráfico supone pérdidas de mercado y, por tanto, reducción de ingresos para el proveedor de servicios. En esta tesis se propone un método para realizar la estimación de tráfico perdido debido a la celda caída.

- **Algoritmos de COC adaptativos**. En esta tesis se presenta una nueva metodología de COC considerando la ventaja del análisis previo. Las actuales soluciones de COC normalmente se centran en modificar un determinado parámetro de control (p.ej., el ángulo de inclinación de antena o la potencia de transmisión de la estación base) en un determinado número de celdas vecinas para solucionar, en la mayoría de los casos, un problema de hueco de cobertura. En esta tesis, se presenta una mejora de la función de COC que solventa las limitaciones de las anteriores soluciones. Esta mejora se obtiene adaptando la función de COC a cada caso particular de celda caída considerando los diferentes efectos que pueden darse en las distintas vecinas. Cuando se detecta un fallo de celda caída, se lleva a cabo un análisis detallado de los efectos causados en las celdas vecinas. A partir de los resultados de este análisis, se determina el conjunto de celdas que llevarán a cabo la compensación y los parámetros de control que se modificarán en cada caso para adaptar la compensación al problema específico de cada celda vecina. Así, la función de COC se centra en mitigar la degradación particular de cada vecina causada por la celda caída.

  En concreto, se proponen tres algoritmos de COC, implementados con lógica difusa, basados en la modificación del ángulo de inclinación de antena y el margen de traspaso. Las modificaciones del ángulo de inclinación de antena se ha utilizado extensamente en los algoritmos de COC presentes en la literatura. Sin embargo, los parámetros de traspaso no se han utilizado previamente con este propósito. Normalmente, la modificación de los parámetros de traspaso se han utilizado en otras funciones SON como la optimización de movilidad o el balance de carga en caso de congestión.

d) Compensación de celda degradada

Los trabajos de compensación del estado del arte tratan de compensar el fallo de celda caída. En esta tesis, se considera la compensación de un fallo diferente al de celda caída. En concreto, el fallo considerado es un problema de cobertura débil debido a una reducción de la potencia de transmisión de la estación base. Esta reducción puede estar causada por problemas de cableado o una configuración errónea de algún parámetro. En esta situación, la celda problemática puede continuar sirviendo tráfico a pesar del fallo por lo que puede formar parte del proceso de compensación. En esta tesis se ha propuesto utilizar el margen de traspaso como parámetro de control para llevar a cabo la compensación. En concreto, la principal contribución en este caso se relaciona con dos aspectos:

- En primer lugar, a diferencia de trabajos anteriores, en esta tesis se ha considerado el fallo de cobertura débil. Además, se propone un método de compensación que pretende mitigar los efectos producidos por este fallo en la celda problemática. Para ello se ha considerado la modificación de parámetros de control de la propia celda problemática como parte del proceso de compensación.

- En segundo lugar, en este trabajo se ha propuesto un algoritmo de compensación basado en la modificación de los márgenes de traspaso de la propia celda problemática y las celdas vecinas. El uso de este parámetro dentro del contexto de la compensación de un fallo es una de las contribuciones importantes de este trabajo.

A.6.2 Publicaciones y proyectos

Las siguientes subsecciones presentas las publicaciones relacionadas con esta tesis.

Revistas

Publicaciones derivadas de esta tesis

[I] I. de-la-Bandera, R. Barco, P. Muñoz and I. Serrano, “Cell Outage Detection Based on Handover Statistics”, *IEEE Communications Letters*, vol. 19, no. 7, pp. 1189-1192, July 2015.

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Publicaciones relacionadas con esta tesis

[VI] P. Muñoz, R. Barco, I. de-la-Bandera, E. J. Khatib, A. Gómez-Andrades and I. Serrano, "Root Cause Analysis based on Temporal Analysis of Metrics toward Self-Organizing 5G Networks", *IEEE Transactions on Vehicular Technology*, Accepted, 2016.

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Proyectos relacionados

Esta tesis ha sido parcialmente financiada por los siguientes proyectos:

- P08-TIC-4052, Junta de Andalucía.

- 8.06/5.59.3721, contrato con Optimi-Ericsson, Junta de Andalucía (Agencia IDEA, Consejería de Ciencia, Innovación y Empresa) y FEDER.
- 8.06/5.59.3722, contrato con Optimi-Ericsson, Junta de Andalucía (Agencia IDEA, Consejería de Ciencia, Innovación y Empresa) y FEDER.
- P12-TIC-2905, Junta de Andalucía.

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