Innovative Methods for Fair Coexistence between LTE and Wi-Fi in Unlicensed Spectrum

Innovatieve methodes voor eerlijke co-existentie tussen LTE en Wi-Fi in licentievrij spectrum

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“As you set out for Ithaka
hope that the voyage is a long one,
full of adventure, full of knowledge.”
Ithaca, October 1911
C.P. Cavafy

«Σα βγεις στον πηγαιμό για την Ιϑάκη,
να εύχεσαι νάναι μακρύς ο δρόμος,
γεμάτος περιπέτειες, γεμάτος γνώσεις.»
Ιϑάκη, Οκτώβρης 1911
Κ.Π. Καβάφης

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List of Acronyms

3

3GPP	3rd Generation Partnership Project

A

ABS	Almost Blank Subframe
AC	Access Category
ACK	Acknowledgement
AC_BE	Access Category - Best Effort traffic
AC_BG	Access Category - Background traffic
AC_VI	Access Category - Video traffic
AC_VO	Access Category - Voice traffic
Adam	Adaptive moment estimation
ADC	Analog-to-Digital Converter
AIFS	Arbitration Inter-Frame Spacing
AP	Access Point
ASA	Authorized Shared Access

B

BPSK	Binary Phase Shift Keying

C

Cat 4	Category 4
CBRS	Citizens Broadband Radio Service
CCA	Clear Channel Assessment
CCE	Central Coordination Entity
CFI	Control Format Indicator
CNN	Convolutional Neural Network
COTS	Commercial off-the-shelf
CP	Cyclic Prefix
CPU	Central Processing Unit
CS	Carrier Sense
CSAT	Carrier Sense Adaptive Transmission
CSIR	Channel State Information at a Receiver
CSMA/CA	Carrier Sensing Multiple Access with Collision Avoidance
CTS	Clear to Send
CW	Contention Window
CWD	Choi-Williams time-frequency distribution

D

D2D	Device-to-Device
DC	Direct Conversion
DCE	Distrributed Coordination Entity
DCF	Distributed Coordinated Function
DFS	Dynamic Frequency Selection
DIFS	DCF Inter-Frame Spacing
DL	Downlink
DwPTS	Downlink Pilot Time Slot

E

ED	Energy Detection
EDCA	Enhanced Distributed Channel Access
EHF	Extremely High Frequency
EPC	Evolved Packet Core
ETSI	European Telecommunications Standards Institute
EUTRAN	Evolved Universal Terrestrial Radio Access Network
EXMIMO2	EXPRESSMIMO2
eICIC	enhanced Inter-Cell Interference Coordination
eMBB	enhanced Mobile Broadband
eNB	evolved NodeB
eWINE	elastic WIreless Networking Experimentation

F

FC	Fully Connected
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FFT	Fast Fourier Transform
FLEX	FIRE LTE testbeds for open EXperimentation
FN	False Negative
FP	False Positive

G

GLOBECOM	GLobal Communications Conference
GP	Guard Period
GPU	Graphics Processing Unit

H

HARQ	Hybrid Automatic Repeat reQuest
HF	High Frequency
HetNets	Heterogeneous Networks

I

I/Q	In-phase and Quadrature
IEEE	Institute of Electrical and Electronics Engineers
IMS	IP Multimedia Subsystem
ISM	Industrial, Scientific and Medical
ISP	Internet Service provider
IT	Information Technology
ITU	International Telecommunication Union
ITU-R	International Telecommunication Union Radiocommunication Sector
IoE	Internet of Everything
IoT	Internet of Things
i.d.d.	Identically Distributed

L

LAA	Licensed Assisted Access
LAN	Local Area Network
LBT	Listen Before Talk
LF	Low Frequency
LSA	Licensed Shared Access
LTE	Long Term Evolution
LTE-U	LTE-Unlicensed

LTF	Long Training Field

M

M2M	Machine-to-Machine
MAC	Medium Access Control
MAN	Metropolitan Area Network
MCS	Modulation and Coding Scheme
MDP	Markov Decision Process
MF	Medium Frequency
MIMO	Multiple-Input Multiple-Output
MPDU	MAC Protocol Data Unit
MVNO	Mobile Virtual Network Operator
MobiHoc	Mobile Ad Hoc Networking and Computing
mLTE-U	muting LTE-U
mMTC	massive Machine Type Communications

N

NFV	Network Function Virtualization
NN	Neural Network
NR	New Radio

O

OAI	OpenAirInterface
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
OTS	Off-The-Shelf

P

PAPR	Peak to Average Power Ratio
PBCH	Physical Broadcast Channel
PCFICH	Physical Control Format Indicator Channel
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PHICH	Physical HARQ Indicator Channel
PHY	Physical
PLCP	Physical Layer Convergence Protocol
PSCH	Primary Synchronization Channel
PSS	Primary Synchronization Signal
PUSCH	Physical Uplink Shared Channel

Q

QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
QoS	Quality of Service

R

RAT	Radio Access Technology
RB	Resource Block
RE	Resource Element
RF	Radio Frequency
RL	Reinforcement Learning
RSPP	Radio Spectrum Policy Programme
RSR	Ratio of Successful Recognition
RTN	Radio Transformer Networks

RTS	Request to Send
ReLU	Rectified Linear Unit

S

SC-FDMA	Single-Carrier Frequency-Division Multiple Access
SDR	Software-Defined Radio
SER	Symbol Error Rate
SHF	Super High Frequency
SIFS	Short Inter-Frame Space
SISO	Single-Input Single-Output
SNR	Signal to Noise Ratio
SRS	Sounding Reference Signal
SSCH	Secondary Synchronization Channel
SSS	Secondary Synchronization Signal
STA	Station
STF	Short Training Field
SVM	Support Vector Machines

T

TBS	Transport Block Size
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TN	True Negative
TP	True Positive
TXOP	Transmission Opportunity

U

U-NII	Unlicensed National Information Infrastructure

UE	User Equipment
UHF	Ultra High Frequency
UL	Uplink
URLLC	Ultra Reliable Low Latency Communications
USRP	Universal Software Radio Peripheral
UpPTS	Uplink Pilot Time Slot

V

VHF	Very High Frequency
VLF	Very Low Frequency

W

WLAN	Wireless Local Area Network
WMM	Wi-Fi Multimedia
WiSHFUL	Wireless Software and Hardware platforms for Flexible and Unified radio and network controL

Samenvatting
– Summary in Dutch –

In de afgelopen jaren is er een enorme technologische groei geweest in het domein van de draadloze communicatie. Mobiele communicatie heeft de manier waarop mensen communiceren, informatie uitwisselen en zich ontspannen grondig veranderd. De evolutie en consolidatie van het Internet der Dingen (IoT) heeft het aantal geconnecteerde toestellen een boost gegeven en er wordt verwacht dat er binnen een aantal jaren ongeveer 50 miljard toestellen online zullen zijn. Dit betekent dat weldra het aantal geconnecteerde toestellen de wereldpopulatie zal overstijgen met een factor 7. Omwille van deze ongeëvenaarde technologische groei zal het frequentiespectrum snel verzadigen. Vaak wordt het spectrum niet optimaal gebruikt. Meer nog, het gelicenseerde spectrum dat wordt gebruikt door mobiele operatoren, wordt schaarser en duurder. Daarom is de mobiele community gestart met het onderzoeken en ontwikkelen van verscheidene oplossingen die voorzien in een flexibeler spectrumbeheer en meer efficiënt spectrumgebruik.

Naast oplossingen zoals carrier aggregatie, massive Multiple-Input Multiple-Output (MIMO) en Licensed Shared Access (LSA), heeft Long Term Evolution (LTE) in het licentievrije spectrum de aandacht getrokken van de research community. Tegenwoordig zijn er verschillende manieren om LTE in licentievrij spectrum te gebruiken, waaronder de uitrol door een mobiele operator en de werking ervan in standalone mode. LTE is een technologie die het spectrum centraal toekent en op een zeer efficiënte manier beheert. Ook is het interessant voor mobiele operatoren om een deel van hun zwaar belaste draadloze netwerken te laten opereren in het licentievrij spectrum om de gebruikerservaring van hun abonnees te verbeteren.

Sinds LTE in het licentievrije spectrum werd voorgesteld, hebben verschillende studies geprobeerd om de impact te onderzoeken van LTE op andere gevestigde technologieën in het licentievrije spectrum, zoals IEEE 802.11 (beter bekend als Wi-Fi), IEEE 802.15.4 en Bluetooth. Meer nog, verscheidene technieken die trachten om de co-existentie tussen LTE en deze technologieën te verbeteren, werden geopperd. Vandaag de dag is Wi-Fi de meest gebruikte technologie in het licentievrije spectrum. Men gebruikt Wi-Fi in talrijke toestellen, zoals smartphones, tablets, PCs, smart TVs, enzovoort. Er wordt verwacht dat zowel Wi-Fi als LTE een sleutelrol zullen spelen in het nieuwe 5G era. *Dit proefschrift focust op het evalueren van de impact van LTE op Wi-Fi en onderzoekt co-existentie- en coöperatietechnieken die een eerlijke en harmonieuze symbiose mogelijk maken* *tussen de twee technologieën in het ongelicenseerde spectrum.*

In het eerste deel van het proefschrift wordt de nodige achtergrondinformatie gegeven in verband met het bestudeerde topic en wordt de impact van traditionele LTE op Wi-Fi geëvalueerd, wanneer beide technologieën opereren in het licentievrije spectrum. We beschouwen traditioneel LTE als de LTE technologie zoals deze oorspronkelijk ontwikkeld is voor werking in een gelicenseerde spectrale band, namelijk zonder de ondersteuning van enig co-existentie mechanisme. Voor deze studie werd commerciële off-the-shelf (COTS) hardware gebruikt om realistische LTE en Wi-Fi verkeer te genereren. Deze studie is uitermate belangrijk om te begrijpen waarom LTE Wi-Fi domineert. De uitkomst van deze studie is waardevol met het oog op de ontwikkeling van co-existentie en coöperatietechnieken die een eerlijke en harmonieuze symbiose mogelijk maken.

Vervolgens onderzoeken we een aantal coöperatietechnieken die het delen van het spectrum kunnen verbeteren, wat moet resulteren in een betere aangeboden gebruikerservaring. Om de verschillende types van technieken die kunnen toegepast worden tussen netwerken zich in elkaars omgeving bevinden te onderscheiden, hebben we een taxonomie opgesteld die een classificatie maakt van de verschillende co-existentie en coöperatietechnieken. Daarna wordt een gedetailleerd overzicht gegeven van de state-of-the-art en de regionale voorschriften inzake licentievrije spectrum. Deze studie geeft een dieper inzicht in de onderzoeksinspanningen van de draadloze onderzoekswereld inzake dit onderwerp en onderstreept de vereisten waaraan moet worden voldaan door co-existentie en coöperatietechnieken om wereldwijd bruikbaar te zijn. De verschillende coöperatiemethodes worden vergeleken op basis van hun verwachte complexiteit en prestatie.

Eén van de hoofddoelen van dit proefschrift, is van een eerlijke verdeling van het spectrum tussen LTE and Wi-Fi netwerken die zich in elkaars buurt bevinden. Derhalve is het zeer belangrijk om metrieken te identificeren die bepalen wanneer co-existentie eerlijk is. We definieren eerlijke co-existentie op een technologie-agnostische wijze, waarbij er meerdere aspecten van de draadloze omgeving in beschouwing worden genomen, zoals het type van de netwerken, het aantal actieve gebruikers van elk netwerk en het dataverkeer die elke gebruiker op het netwerk wil plaatsen.

Verder wordt in dit proefschrift een oplossing voorgesteld en genalyseerd een aanpasbare co-existentie methode die tegemoet komt aan het grootste minpunt van het LTE Licensed-Assisted Access (LAA) mechanisme dat wordt gestandaardiseerd door het 3rd Generation Partnership Project (3GPP). Volgens de LTE LAA standaard, mag LTE uitzenden in licentievrije spectrum tijdens vooropgestelde periodes ("transmit oportuityöf TXOP genoemd), afhankelijk van de prioriteitsklasse die wordt gebruikt. Deze methode kan resulteren in oneerlijke co-existentie met Wi-Fi, wanneer deze laatste geen gebruik maakt van frame-aggregatie. De co-existentie methode die wij in dit proefschrift voorstellen noemen we muting LTE-U (mLTE-U) en bouwt verder op elementen van LTE LAA. mLTE-U gebruikt een aanpasbare TXOP, met aansluitend een flexibele muting periode. De muting periode kan benut worden door andere netwerken die zich in de buurt bevinden om toegang te krijgen tot het draadloze medium. Verscheidene co-existentie scenarios met variabele densiteit van LTE en Wi-Fi netwerken worden geanalyseerd met het oog op het evalueren van co-existentie tussen mLTE-U en Wi-Fi.

Een draadloze omgeving is niet deterministisch en wijzigt continu op een zeer dynamische wijze. Om in deze omstandigheden het spectrum eerlijk te verdelen, ongeacht de dynamiek van de draadloze omgeving, is het noodzakelijk dat het co-existentie mechanisme autonoom zijn parameters kan aanpassen. Daartoe werd het mLTE-U schema uitgebreid met een Q-learning techniek die gebruikt wordt voor de zelf-adaptatie van de combinatie van TXOP en muting periode met het oog op het bieden van eerlijke co-existentie. De efficiëntie van de voorgestelde oplossing wordt geëvalueerd voor verschillende interessante co-existentie scenario's. Daarenboven wordt de prestatie van Q-learning vergeleken met andere conventionele methodes, hetgeen aantoont dat Q-learning superieur is ten opzichte van minder complexe mechanismes.

Om zich te kunnen aanpassen aan de veranderingen van een draadloze omgeving, is het noodzakelijk om deze eerst te identificeren. Heel wat informatie kan verkregen worden van de draadloze omgeving en kan gebruikt worden door de co-existentie methode. Zulke informatie kan onder andere bestaan uit het type van de netwerken die zich in elkaars buurt bevinden, de bezettingsgraad van het draadloze kanaal door elke technologie, het aantal nodes die zenden en de belasting van elke node. Om dit te verwezenlijken, wordt een Convolutional Neural Network (CNN) geïntroduceerd dat in staat is om LTE en Wi-Fi transmissies te identificeren. Het voorgestelde CNN kan eveneens het 'hidden terminal effect' detecteren dat wordt veroorzaakt door meerdere LTE, meerdere Wi-Fi of gelijktijdige LTE and Wi-Fi tranmissies. Het ontwikkelde CNN werd getraind en gevalideerd voor twee verschillende signaalrepresentaties, namelijk In-phase en Quadrature (I/Q) samples en een frequentiedomein voorstellling door middel van Fast Fourier Tranform (FFT). De nauwkeurigheid van de classificatie van de getrainde CNNs werd getest voor verschillende Signal to Noise Ratio (SNR) waarden. Er werd aangetoond hoe een co-existentie methode, zoals mLTE-U de verkregen informatie van de CNN kan benutten om de co-existentie te verbeteren.

Samenvattend, het werk dat werd uitgevoerd in dit proefschrift behandelt verschillende aspecten die te maken hebben met een eerlijke werking van LTE in het licentievrije spectrum in relatie tot Wi-Fi. Het onderzoek belicht een uitgebreide waaier aan topics, waaronder de evaluatie van de impact van traditionele LTE op Wi-Fi, een overzicht van co-existentie en coöperatietechnieken, de definitie van eerlijkheid in het licentievrije spectrum, automatische en autonome configuratie van co-existentie mechanismen en de identificatie van netwerken die zich in elkaars buurt bevinden. Dit onderzoek heeft geresulteerd in verschillende artikels en papers die gepubliceerd zijn ininternationale journals and conferenties. Dit doctoraat levert een solide bijdrage in zijn domein dat kan aanzien worden als een hoeksteen in de volgende generatie van draadloze netwerken.

Summary

Over the last years, the technological growth has resulted in a tremendous increase in the domain of wireless communications. Mobile communications have changed decisively the way people communicate, exchange information and experience entertainment. The evolution and consolidation of the Internet of Things (IoT) has further boosted the number of interconnected devices. It is expected that in a few years there will be about 50 billion devices online. This means that soon, the number of interconnected devices will exceed the number of humans almost by sevenfold. Due to this unparalleled technological growth, the frequency spectrum becomes saturated often leading to sub-optimal use of the spectrum. Additionally, the licensed spectrum used by the mobile operators becomes scarce and expensive. Hence, the mobile community has started investigating solutions that can enable more flexible spectrum management and more optimal spectrum usage. As a result, several solutions are currently being investigated and developed.

Solutions like carrier aggregation, massive Multiple-Input Multiple-Output (MIMO) and Licensed Shared Access (LSA), and operation of Long Term Evolution (LTE) in unlicensed spectrum has significantly attracted the attention of the research community. Today, there are different approaches for the use of LTE in unlicensed spectrum, including the deployment by a mobile operator and the operation in standalone mode. LTE is a technology that is capable to manage the assigned spectrum in a very efficient way. Furthermore, the mobile operators may opportunistically offload their heavily-loaded networks from the licensed spectrum to the unlicensed spectrum, enhancing the user-experience of their subscribers.

Since the LTE operation in unlicensed spectrum has been proposed, studies attempted to investigate the impact of LTE on other well-established technologies in unlicensed spectrum, such as IEEE 802.11 (a.k.a Wi-Fi), IEEE 802.15.4 and Bluetooth. Moreover, several techniques that target to enhance the coexistence between LTE and these technologies have been proposed. In our days, Wi-Fi is the most commonly used technology in unlicensed spectrum. People use Wi-Fi in numerous devices, such as smartphones, tablets, personal computers, smart TVs, etc. Wi-Fi together with LTE is expected to play a key role in the new 5G era. *This dissertation focuses on evaluating the impact of LTE on Wi-Fi and investigates coexistence and cooperation techniques that can enable fair and harmonious cohabitation of the two technologies in the unlicensed spectrum.*

The first part of this dissertation presents background information that introduces the reader to the studied topic and it evaluates the impact that traditional LTE can have on Wi-Fi, when both technologies operate in unlicensed spectrum. By the

term traditional LTE, we mean the LTE technology as it was initially designed for operation in licensed bands, namely without incorporating any coexistence mechanism. For the purposes of this study, commercial off-the-shelf (COTS) hardware has been used to generate real LTE and Wi-Fi traffic. This study is necessary to understand the reasons why LTE dominates Wi-Fi. The outcome of this study is beneficial for the design of coexistence and cooperation techniques that can enable harmonious and fair cohabitation.

Next, we investigate a series of cooperation techniques that can enhance spectrum sharing and offered user-experience. In order to distinguish the different types of techniques that can be applied between co-located networks, we provide a taxonomy that differentiates the coexistence and cooperation techniques. Then, a detailed presentation of the state of the art is given together with an overview of the regional requirements for the unlicensed spectrum. This study further analyses research efforts of the wireless community on this subject and highlights the requirements that must be satisfied by a coexistence or cooperation mechanism in order to be applicable worldwide. Several cooperation schemes are compared in terms of expected complexity and performance.

One of the main goals of the work described in this dissertation is to provide fair spectrum sharing between co-located LTE and Wi-Fi networks. Hence, it is very important to identify the metrics that render coexistence fair. We define fair coexistence in a technology-agnostic way, taking multiple aspects of the wireless environment into account, such as the type of the co-located networks, the number of the active users of each network, as well as the amount of data each user has to transmit.

This dissertation continues by proposing and studying an adaptive coexistence scheme that overcomes the biggest drawback of the LTE Licensed-Assisted Access (LAA) mechanism that is standardized by the 3rd Generation Partnership Project (3GPP). According to LTE LAA, LTE may transmit in unlicensed spectrum for predefined transmission opportunity (TXOP) periods, based on the priority class that is used. This behavior may cause unfair coexistence with Wi-Fi, when Wi-Fi does not use or supports frame aggregation. The proposed coexistence scheme is named muting LTE-U (mLTE-U) and builds on elements of LTE LAA. mLTE-U uses an adaptable TXOP, followed by an adaptable muting period. The muting period can be exploited by other co-located networks to gain access to the wireless medium. Several coexistence scenarios for variable density of LTE and Wi-Fi networks are examined to evaluate the coexistence between mLTE-U and Wi-Fi.

The wireless environment is non-deterministic and changes continuously and dynamically. In order to guarantee fairness regardless of the changes in the wireless environment, a coexistence scheme must be able to adapt its parameters autonomously. To this end, the mLTE-U scheme is enhanced with a Q-learning technique that is used for self-adaptation of the TXOP and muting period combinations that can provide fair coexistence. The efficiency of the proposed solution is evaluated for several coexistence scenarios of high interest. Additionally, the performance of Q-learning is compared with other conventional schemes revealing its superiority over less complex mechanisms.

In order to be able to adapt to the changes of the wireless environment, it is necessary first to identify them. Several information can be obtained by the wireless environment and can be used by a coexistence scheme. Such information may include the type of the co-located networks, the channel occupation of each technology, the number of transmitting nodes and the load of each node. To identify the wireless environment, a Convolutional Neural Network (CNN) that is able to identify LTE and Wi-Fi transmissions is introduced. The proposed CNN can also identify the hidden terminal effect that is caused by multiple LTE, multiple Wi-Fi or concurrent LTE and Wi-Fi transmissions. The designed CNN has been trained and validated for two different signal representations, namely In-phase and Quadrature (I/Q) samples and frequency domain representation through Fast Fourier Transform (FFT). The classification accuracy of the trained CNNs is tested for several Signal to Noise Ratio (SNR) values. It is shown how a coexistence scheme, such as mLTE-U, can exploit the obtained information from the CNN to enhance the provided coexistence.

In summary, the work conducted within this dissertation deals with several studies and solutions regarding the fair LTE operation in unlicensed spectrum when co-located with Wi-Fi networks. The research covers a wide range of topics, including: evaluation of the impact of traditional LTE on Wi-Fi, proposal of cooperation and coexistence techniques, definition of fairness in unlicensed spectrum, automatic and autonomous configuration of coexistence mechanisms and identification of coexisting networks. This research resulted in several articles and papers that have been published in international journals and conferences respectively. This PhD makes a solid contribution to its domain that can be used as a cornerstone for the next generation of wireless networks.

1

Introduction

"All men by nature desire knowledge."

– Aristotle (384 BC - 322 BC)

This chapter gives an overview of the performed work in the context of this dissertation. The operation of Long Term Evolution (LTE) networks in the unlicensed spectrum is a key element towards the rising 5G era. However, it poses several challenges that must be addressed towards a harmonious coexistence between LTE and other well-established technologies in unlicensed spectrum, such as IEEE 802.11 (also known as Wi-Fi). These challenges include among others interference management, fair sharing of the wireless resources and Quality of Service (QoS) guarantees. LTE and Wi-Fi are two technologies that were not initially designed to work together, as they target to fulfill different requirements (e.g. traffic requirements), operating in different spectral conditions. LTE was initially designed to operate in a licensed band, and follows a central approach for the allocation of spectrum in an exclusive licensed spectrum band, while Wi-Fi is being implemented to operate into the unlicensed spectrum in the presence of other devices and networks. Wi-Fi follows a distributed approach for accessing the shared unlicensed spectrum, and consequently Wi-Fi devices must contend with other devices to access the wireless medium before a transmission. This dissertation aims to deal with these challenges, focusing on the provision of harmonious coexistence and fair spectrum sharing techniques between co-located LTE and Wi-Fi networks.

The remainder of this chapter gives a brief introduction to the challenges that must be overcome in order to provide fair coexistence between these two widespread wireless technologies and as such to realize an enhanced user experience. Next, it highlights the conducted research work, summarizes the main contributions and outlines the structure of this dissertation. Finally, it provides a list of related authored publications.

1.1 Research Challenges

Over the last years, a big part of the mobile community has focused on investigating solutions that can improve the coexistence of LTE and Wi-Fi in the unlicensed spectrum [1]. This dissertation tackles a number of research challenges that emerge when these two wireless technologies operate in the same wireless environment using the same frequency band. The main focus of this dissertation is to study and enhance the coexistence of LTE and Wi-Fi in the unlicensed spectrum in a fair manner. The first step towards a harmonious coexistence is to study the impact of LTE on Wi-Fi as well as its causes, when the two wireless technologies operate in the way that they were initially designed (Section 1.1.1). The next important step is to define what is fair coexistence and how it can be provided by a coexistence mechanism (Section 1.1.2). Afterwards, we can investigate coexistence and cooperation techniques that can enable the desired fair spectrum sharing (Section 1.1.3). The proposed coexistence schemes can be enhanced by techniques that enable autonomous and automatic configuration of their coexistence parameters (Section 1.1.4). Additionally, the coexistence schemes can be improved by techniques that provide information about the identity of the coexisting networks, so that the schemes can be adapted to the dynamic changes of the wireless environment (Section 1.1.5). The rest of this section gives an overview of the research challenges tackled in this dissertation.

1.1.1 Investigate the impact of traditional LTE on Wi-Fi

Before studying techniques that can enable fair coexistence, it is important to investigate the impact that traditional LTE can have on Wi-Fi. Traditional LTE can be considered as an LTE network that does not use any mechanism to adapt its transmission behavior when it is co-located with other wireless technologies and uses the same frequency band. Such LTE system is based on LTE Release 12 [2] and below, as since Release 13, LTE Licensed Assisted Access (LAA) procedure has been standardized. Previous studies [3] have examined the impact that Wi-Fi can have on the performance of LTE, showing that LTE performance is not affected or suffers only a minor degradation that is considered to be negligible. This is to be expected as Wi-Fi based on the Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) mechanism must estimate the availability of the wireless medium before a transmission, in contrast to LTE that schedules transmissions without performing any channel assessment. As a result, Wi-Fi will be forced to continuously backoff having an insignificant impact on LTE. Hence, this dissertation focuses on the performance degradation of Wi-Fi in the presence of LTE.

Investigating the impact of LTE on Wi-Fi allows us to better understand the reasons that render traditional LTE a harmful neighbor to Wi-Fi. Additionally, it will allow us to realize the characteristics and the properties that a cooperation or coexistence mechanism should have in order to provide equal channel opportunities to both technologies.

1.1.2 Definition of fair coexistence

The main goal of this dissertation is to provide fair spectrum sharing between the co-located LTE and Wi-Fi networks. But what are the metrics that render the coexistence between different technologies fair? On first thought, a fair mechanism should be able to give to both LTE and Wi-Fi equal opportunities to the medium. But how equally fair would this approach be in case that the LTE part would consist of multiple end-devices with large traffic flows, while the Wi-Fi part would consist of a single end-device that rarely transmits? It becomes clear, there are multiple aspects that should be taken into account for the definition of fair coexistence such as the type and number of co-located nodes, as well as the amount of data that each node has to transmit.

Defining fair coexistence is a complex task as several parameters need to be taken into consideration in order to avoid unbalanced coexistence. Tackling this challenge will help to define the targets that the designed coexistence mechanism should reach in order to meet the desired Quality of Service (QoS) requirements and to satisfy the user experience.

1.1.3 Fair coexistence and cooperation techniques that respect the regional regulations

After understanding and evaluating the impact of LTE on Wi-Fi and defining the fairness between coexisting networks, the next big challenge is to propose techniques that are able to minimize this impact and guarantee fair sharing of the spectral resources. An initial step is to classify these techniques into two big categories named coexistence and cooperation techniques.

By coexistence, we characterize a technique that aims to improve the symbiosis between co-located networks, but without the exchange of any information between the different technologies. Such techniques require careful design so that the regional regulations are respected and fairness is guaranteed. A technique of this nature must have an altruistic behavior, meaning that it should provide to neighboring networks the required opportunities to the medium. Moreover, it must be able to adapt to the changes of the wireless environment, such as the number of co-located networks, the amount of traffic that has to be transmitted, etc.

On the other hand, the cooperation term refers to techniques that allow the collaboration between the participating technologies to achieve fair spectral sharing via the exchange of specific information between the cooperating networks. The implementation of this kind of techniques can be very challenging. The communication protocol between the two different technologies requires careful design in order to minimize the information exchange overhead and to account for the special characteristics and requirements of each technology. Again, the regional regulations must be respected so that the technique can be applied worldwide.

1.1.4 Automatic and autonomous configuration of coexistence mechanisms

It is important for a coexistence mechanism to be able to adapt its coexistence parameters autonomously and automatically in order to provide the desired fairness, even when the conditions of the wireless environment change. This requires that the system must be able to learn the environment and make appropriate decisions for maintaining the fair coexistence. Ideally, this must be done without the need of a predefined model of the environment.

Reinforcement learning, a branch of machine learning, can play a significant role in automatic and autonomous configuration of coexistence parameters. It provides methodologies that use statistical techniques to allow a system to learn how to perform a specific action at a specific state, without being explicitly programmed to act this way. Enhancing the coexistence technique of a wireless system with machine learning in order to perform autonomously specific actions and adapt its behavior is an important challenge that must be overcome towards a robust coexistence solution.

1.1.5 Identification of the coexisting networks

The wireless environment is a non-deterministic environment that changes continuously and dynamically. These changes may refer to the number and type of the co-located wireless networks, the amount of traffic that is transmitted by each network, the number of active users of each network, etc. A coexistence scheme should be flexible and able to adapt its parameters based on these changes in order to provide fair coexistence. Technology recognition can determine how a band is being utilized. Unfortunately, most wireless systems in real life only recognize their own signals, as the implementation of multiple technology-specific algorithms on one system is very complex and costly [4].

Over the last years, the domain of artificial intelligence has been significantly evolved. Deep learning has been applied in several aspects of daily life (e.g. image recognition and translation) having remarkable results that many times outperform human levels of accuracy [5]. Incorporating artificial intelligence mechanisms to wireless networks can be a key-element towards the new generation of networks. Deep learning and more specific Convolutional Neural Networks (CNN) can assist in extracting valuable information from the wireless environment. The output of the CNN can be used by a wireless network to adapt the parameters of its coexistence technique. Incorporating CNN and more generally artificial intelligence into the coexistence mechanism of a wireless network is a big challenge and by solving it the performance of coexisting wireless technologies can be significantly boosted.

1.2 Outline

This dissertation is composed of a number of publications that were realized within the scope of this PhD. The selected publications provide an integral and consistent overview of the work performed. The different research contributions are listed in Section 1.3 and the complete list of publications that resulted from this work is presented in Section 1.4. Within this section, we give an overview of the conducted research and explain how the different chapters are linked together.

Chapter 2 gives an overview of the technical background of this dissertation. The challenges in the radio spectrum, where LTE and Wi-Fi coexistence in the frequency domain takes place, is introduced. Subsequently, the chapter presents the different approaches for the LTE operation in unlicensed spectrum. Next, the two technologies that are examined in this dissertation namely LTE and Wi-Fi are described, highlighting the aspects that may cause harmful coexistence. This way, the characteristics that a coexistence technique should have in order to eliminate the negative impact are realized. Then, the importance of coexistence and cooperation mechanisms that enable fair spectrum sharing between the two technologies is pointed out.

Chapter 3 investigates in detail the impact of traditional LTE operating in unlicensed spectrum on Wi-Fi, using real hardware equipment. It starts discussing the role that LTE in unlicensed spectrum can play in solving the 1000x traffic increase challenge. This challenge refers to the expected increase of traffic by factor of 1000 by 2020. The main reason of the dominance of LTE over Wi-Fi is that Wi-Fi must ensure the channel's availability before a transmission, while traditional LTE transmits using a central scheduler, assuming that it can use the spectrum exclusively. The chapter continues by describing the equipment that has been used and the experimentation setup. Subsequently, the obtained experimentation results are presented in detail. According to the results, the arbitrary LTE transmission will force Wi-Fi to backoff if the transmission power of LTE is above a certain threshold or it will interfere to Wi-Fi transmissions if the transmission power is below this threshold. Additionally, it has been observed that if the LTE transmission power surpasses the sensitivity threshold of a Wi-Fi station (STA), then the STA disassociates from the Access Point (AP). This way LTE can completely eliminate Wi-Fi.

After investigating the impact of traditional LTE on Wi-Fi and the reasons behind the resulting unfair coexistence, we investigate different cooperation techniques that can assist in improving the spectrum sharing in Chapter 4. First, this chapter presents a taxonomy of techniques that can be applied among co-located LTE and Wi-Fi networks. Next, the state of the art regarding the coexistence of the two technologies is extensively analyzed and an overview of the regional requirements for the unlicensed spectrum is presented. Such a study is useful to reveal the intentions of the wireless community on the investigated subject and better understand the requirements that must be fulfilled by a cooperation algorithm in order to be applicable worldwide. Further, several cooperation schemes are proposed, which are distinguished into two different categories, depending on whether direct cooperation via in-band energy level patterns or indirect cooperation via a third-party entity is used. All the proposed schemes are compared based on their expected synchronization requirements, their complexity and their expected performance.

In chapter 5, an adaptive LTE Listen Before Talk (LBT) scheme that builds on elements of LTE LAA and can provide fair coexistence with Wi-Fi is proposed and studied in detail. This scheme targets to enhance the fairness provided by LTE LAA. The proposed mechanism is named muting LTE-U (mLTE-U) and according to it, an LTE network uses a variable Transmission Opportunity (TXOP), followed by a variable muting period. The muting period can be exploited by co-located Wi-Fi or mLTE-U networks in order to access the channel. Based on changes of the wireless environment, the TXOP and the muting period of LTE can be adapted to sustain efficient coexistence. The chapter describes briefly the LTE and Wi-Fi characteristics and gives an overview of the related work regarding the coexistence between the two technologies. From this discussion the coexistence problem is defined and the proposed solution of mLTE-U is presented. Subsequently, the chapter discusses the challenge of fairness in unlicensed spectrum and how the wireless resources should be shared among the different co-located networks in order to achieve fair coexistence. The simulation environment that is used to evaluate the mLTE-U scheme in terms of coexistence with Wi-Fi is described. Then, different simulation scenarios of high interest are discussed in detail. The investigated scenarios include low mLTE-U and Wi-Fi density deployment, dense mLTE-U deployment, dense Wi-Fi deployment, dense mLTE-U and Wi-Fi deployment, as well as a mobile scenario. The chapter continues by presenting the obtained performance evaluation results for every scenario. From the obtained results it has been revealed that for each scenario multiple configurations of TXOP and muting period can be used. Hence, we discuss ways to automatically select the parameters for achieving fair coexistence and an initial algorithm is proposed.

Chapter 6 takes the work performed in Chapter 5 a step further and studies the system model of the mLTE-U scheme in coexistence with Wi-Fi. Furthermore, mLTE-U is enhanced with a Q-learning technique that is used for autonomous selection of the appropriate TXOP and muting period combinations to realize fair coexistence between the co-located networks. The chapter presents the related work that has been done regarding LTE and Wi-Fi coexistence and how Q-learning has been used towards coexistence enhancement. Next, the proposed solution is presented, followed by a detailed description and analysis of the system model. The chapter continues by defining fairness as equal sharing of spectrum in a technology-agnostic way and by formulating the problem of TXOP and muting period selection towards the achievement of the desired fairness. The proposed enhancement of mLTE-U scheme with Q-learning is analyzed in detail, followed by the description and analysis of the simulation environment. Additionally, the performance of the system is evaluated for several scenarios of high interest, while the performance of Q-learning is compared with other conventional schemes.

The wireless environment is a non-deterministic and dynamically changing environment. Hence, in order to enable fair coexistence, some specific information should be extracted from it such as the type of the co-located networks, the channel occupation of each wireless technology, the number of transmitting nodes and the amount of data that each node has to transmit. Towards this direction, Chapter 7 introduces a CNN that can be used to enable the identification of co-located LTE and Wi-Fi networks. The trained CNN can be used to identify LTE and Wi-Fi transmissions. Furthermore, it can identify hidden terminal effect caused by simultaneous LTE transmissions, simultaneous Wi-Fi transmissions and concurrent LTE and Wi-Fi transmissions. For the training and validation of the CNN, Commercial off-the-shelf (COTS) hardware and open-source software equipment have been used. The designed CNN has been trained and validated using two wireless signal representations, namely In-phase and Quadrature (I/Q) samples and frequency domain representation through Fast Fourier Transform (FFT). Furthermore, the classification accuracy of the trained CNNs is tested for several Signal to Noise Ratio (SNR) values. The experimentation results show that the performance of the CNN depends on the data representation that is used to train the network. More specifically, the FFT representation can offer higher classification accuracy compared to I/Q samples, especially for low SNR values. The chapter also demonstrates how the obtained information from the CNN can be exploited by the mLTE-U scheme.

Finally, Chapter 8 completes the dissertation, by summarizing the main results and concluding the performed work. Furthermore, an outlook on the future regarding the coexistence of LTE with other wireless technologies is given.

Table 1.1 lists the research challenges that are highlighted in Section 1.1 and indicates which challenges are targeted in each chapter. This can assist the reader in browsing this dissertation.

Table 1.1: An overview of the targeted research challenges per chapter

Research Challenge	**Chapter 3**	**Chapter 4**	**Chapter 5**	**Chapter 6**	**Chapter 7**
Impact of LTE on Wi-Fi	●				
Definition of fair coexistence			●	●	
Coexistence and cooperation techniques		●	●	●	●
Autonomous configuration			●	●	●
Identification of coexisting networks					●

1.3 Research Contributions

In Section 1.1, the problems and research challenges for LTE operation in unlicensed spectrum towards fair coexistence with Wi-Fi are discussed. These challenges are tackled in the remainder of this dissertation. The target of this PhD dissertation is to study the problem of enabling fair coexistence between LTE and Wi-Fi.

In the following list, the research contributions of this dissertation are presented on a per chapter basis:

- Impact evaluation of traditional LTE on Wi-Fi for both throughput and round trip latency performance (Ch. 2).
  - Study of the LTE and Wi-Fi characteristics of the Physical (PHY) and Medium Access Control (MAC) layer that cause harmful coexistence when no coexistence or cooperation mechanism is applied.
  - Experimentation using open-source software running on real hardware equipment that is available at the imec iLab.t wireless testbed [1].
  - Performance evaluation using three different levels of LTE signal power that correspond to three different levels of LTE interference.
  - Evaluation of the impact that both LTE control signals and LTE data transmissions can have on Wi-Fi for each LTE signal power level.

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[1] https://doc.ilabt.imec.be/ilabt-documentation/

- Cooperation techniques that can be applied between LTE and Wi-Fi in unlicensed spectrum towards fair spectrum sharing (Ch. 3).
    - Classification of techniques that can be applied on co-located LTE and Wi-Fi networks.
    - Detailed analysis of the current state of the art regarding LTE in the unlicensed spectrum and Wi-Fi.
    - Analysis of the different concepts of cooperation between LTE and Wi-Fi and proposal of potential techniques that can be applied for realizing each concept.
    - Comparison and feasibility of the different proposed concepts.
- Adaptive LTE LBT scheme towards fair coexistence with Wi-Fi (Ch. 4).
    - Definition of fairness as equal sharing of the wireless resources in a technology agnostic way.
    - Problem definition and verification by evaluating the coexistence between LTE LAA and Wi-Fi, when Wi-Fi operates in a traditional way, meaning that it does not support or it does not use frame aggregation.
    - Proposal of an adaptive LTE transmission scheme that uses a variable TXOP followed by a variable muting period. The proposed scheme estimates the channel state before a transmission to ensure its availability.
    - Evaluation of the proposed scheme through simulations.
    - Propose an initial algorithm for the selection of the TXOP and muting period combinations that can offer fair coexistence between LTE and Wi-Fi.
- Q-learning scheme for fair coexistence between LTE and Wi-Fi (Ch. 5).
    - Description and analysis of the system model for the proposed mLTE-U scheme in coexistence with Wi-Fi or other mLTE-U networks.
    - Discussion about fair coexistence in unlicensed spectrum.
    - Problem formulation of mLTE-U TXOP and muting period selection towards fair spectrum sharing.
    - Use of Q-learning mechanism for optimal and autonomous selection of mLTE-U TXOP and muting period towards fair coexistence.
    - Performance evaluation of the proposed mLTE-U coexistence scheme with and without using Q-learning mechanism through simulations.

  - Comparison of Q-learning with conventional selection mechanisms such as random selection and round-robin.

- Enhancing the Coexistence of LTE and Wi-Fi in Unlicensed Spectrum Through Convolutional Neural Networks (Ch. 6).
  - Brief introduction to CNN in order to give to the reader the necessary background of the topic.
  - A CNN is designed and trained to identify LTE and Wi-Fi transmissions in unlicensed spectrum.
  - Interfering LTE and Wi-Fi transmissions as a result of hidden terminal effect can be identified. These interfering transmissions include concurrent LTE transmissions, concurrent Wi-Fi transmissions as well as simultaneous LTE and Wi-Fi transmissions.
  - The designed CNN has been trained and validated using two wireless signal representations named I/Q samples and frequency domain representation through FFT.
  - For the training and validation of the CNN, COTS hardware and open-source software have been used.
  - The classification accuracy of the trained CNNs is tested for several SNR values.
  - The obtained information by the CNN is exploited by mLTE-U scheme to enhance the coexistence between LTE and Wi-Fi.

1.4 Publications

The research results obtained during the PhD research have been published in several scientific journals and presented at a series of international conferences. The following list provides an overview of the publications during my PhD research.

1.4.1 Publications in international journals (listed in the ISI Web of Science [2])

1. **Vasilis Maglogiannis**, Dries Naudts, Adnan Shahid, Spilios Giannoulis, Eric Laermans and Ingrid Moerman. *Cooperation techniques between LTE in unlicensed spectrum and Wi-Fi towards fair spectral efficiency.* Published in the special issue on ’Cognitive Radio Sensing and Sensor Networks’ in

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[2] The publications listed are recognized as ‘A1 publications’, according to the following definition used by Ghent University: A1 publications are articles listed in the Science Citation Index Expanded, the Social Science Citation Index or the Arts and Humanities Citation Index of the ISI Web of Science, restricted to contributions listed as article, review, letter, note or proceedings paper.

the MDPI Sensors Journal, Volume 17, Issue 9, Article Number 1994, 31 August 2017.

2. **Vasilis Maglogiannis**, Dries Naudts, Adnan Shahid and Ingrid Moerman. *An adaptive LTE listen-before-talk scheme towards a fair coexistence with Wi-Fi in unlicensed spectrum.* Published in the Telecommunication Systems Journal, Volume 68, Issue 4, pp. 701-721, 10 January 2018.

3. **Vasilis Maglogiannis**, Dries Naudts, Adnan Shahid and Ingrid Moerman. *A Q-learning Scheme for Fair Coexistence Between LTE and Wi-Fi in Unlicensed Spectrum.* Published in the IEEE Access Journal, Volume 6, pp. 27278-27293, 15 May 2018.

4. Adnan Shahid, **Vasilis Maglogiannis**, Kwang Soon Kim, Eli De Poorter and Ingrid Moerman. *Energy-efficient resource allocation for ultra-dense licensed and unlicensed dual-access small cell networks.* Submitted to the IEEE Transactions on Mobile Computing Journal.

5. **Vasilis Maglogiannis**, Adnan Shahid, Dries Naudts, Eli De Poorter and Ingrid Moerman. *Enhancing the Coexistence of LTE and Wi-Fi in Unlicensed Spectrum Through Convolutional Neural Networks.* To be submitted.

1.4.2 Publications in international conferences (listed in the ISI Web of Science [3])

1. **Vasilis Maglogiannis**, Dries Naudts, Pieter Willemen and Ingrid Moerman. *Impact of LTE Operating in Unlicensed Spectrum on Wi-Fi Using Real Equipment.* Published in IEEE Global Communications Conference (GLOBECOM), pp. 1–6, 4–8 December 2016.

1.4.3 Publications in other international conferences

1. **Vasilis Maglogiannis**, Dries Naudts, Ingrid Moerman, Nikos Makris and Thanasis Korakis. *Demo: Real LTE experimentation in a controlled environment.* Published in 6e ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc), pp. 413–414, 22–25 June 2015.

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[3] The publications listed are recognized as ‘P1 publications’, according to the following definition used by Ghent University: P1 publications are proceedings listed in the Conference Proceedings Citation Index - Science or Conference Proceedings Citation Index - Social Science and Humanities of the ISI Web of Science, restricted to contributions listed as article, review, letter, note or proceedings paper, except for publications that are classified as A1.

1.4.4 Book Chapters

1. Nikos Makris, Thanasis Korakis, **Vasilis Maglogiannis**, Dries Naudts, Navid Nikaein, Giorgos Lyberopoulos, Eleni Theodoropoulou, Ivan Seskar, Cesar Augusto Garcia Perez, Pedro Merino Gomez, Milorad Tosic, Nenad Milosevic and Spiros Spirou. *Platform for 4G/5G wireless networking research, targeting the experimentally-driven research approach - FLEX -*. Published in the book with title Building the future Internet through FIRE, pp. 111–153, 2016.

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2

Background

This chapter introduces the technical background of this dissertation. First, the context of Long Term Evolution (LTE) and Wi-Fi coexistence is given. The radio spectrum, where the coexistence in frequency domain takes place, is briefly introduced. Then, the LTE operation in unlicensed spectrum and its dominant approaches are presented. The two technologies that are examined in this dissertation, LTE and Wi-Fi, are described, highlighting their characteristics and differences that must be taken into account during the design of a coexistence or a cooperation mechanism. Subsequently, the importance of coexistence and cooperation mechanisms that enable fair spectrum sharing between the two technologies is highlighted.

2.1 Wireless spectrum challenges

Nowadays, the technological growth combined with the ubiquitous Internet has played a significant role in increasing the number of interconnected devices. As a result, over the last years, the amount of wireless traffic is increasing dramatically. The Internet, as we know it today, changes rapidly and becomes the Internet of Everything (IoE). According to Cisco, one of the largest vendors in Information Technology (IT) and networking products: *"The IoE is bringing together people, process, data, and things to make networked connections more relevant and valuable than ever before - turning information into actions that create new capabilities, richer experiences, and unprecedented economic opportunity for businesses,* *individuals, and countries."* [1]. As it can be seen in Figure 2.1, it is expected that by 2020, about 50 billion devices will be interconnected [2], corresponding to 6.58 connected devices per person according to the estimated world population.

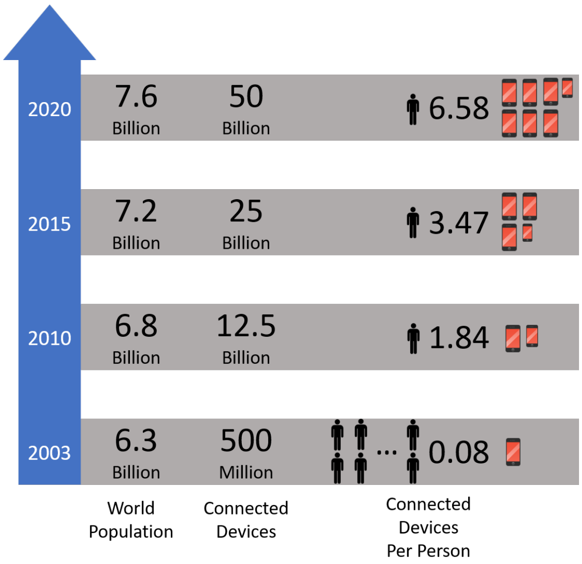

Figure 2.1: The rapid increment of the connected devices globally in relation to the world population

The wireless exchange of information among this tremendous amount of devices brings several challenges that the wireless community has to deal with. One of the most important challenges is the availability of the wireless spectrum. The global mobile data traffic will increase nearly eightfold between 2015 and 2020, reaching 30.6 exabytes per month by 2020 [3]. It becomes clear that in order to satisfy this massive amount of traffic more spectrum is required, while the available spectral resources must be managed more efficiently.

2.1.1 Radio spectrum

The radio spectrum is one of the key-elements of wireless communication. It is a part of the electromagnetic spectrum and it expands from $3kHz$ to $300GHz$ ($3THz$) [4]. Table 2.1 shows the frequencies of the radio spectrum and the most common uses per frequency. The electromagnetic waves in this frequency range are called radio waves. In order to limit interference between different users, the transmission of radio waves is strictly regulated by national laws. These laws are coordinated by an international body, the International Telecommunication Union (ITU) [5]. The mobile operators are obligated to obtain exclusive spectrum li-

Table 2.1: The radio spectrum frequencies and the most common uses cases per frequency

Designation	Frequency	Common uses
Very Low Frequency (VLF)	$3kHz - 30kHz$	Underwater communications
Low Frequency (LF)	$30kHz - 300kHz$	AM radio
Medium Frequency (MF)	$300kHz - 3MHz$	AM radio
High Frequency (HF)	$3MHz - 30MHz$	AM radio, long distance aviation communications
Very High Frequency (VHF)	$30MHz - 300MHz$	FM radio, television, short range aviation communications, weather radio
Ultra High Frequency (UHF)	$300MHz - 3GHz$	television, mobile phones, wireless networks, Bluetooth, satellite radio, GPS
Super High Frequency (SHF)	$3GHz - 30GHz$	satellite television, satellite radio, radar systems, radio astronomy
Extremely High Frequency (EHF)	$30GHz - 300GHz$	radio astronomy, full body scanners

censes from the state government in which they are allowed to operate in order to mitigate interference between the different network deployments. Due to the fast growth of the wireless technologies during the last years, more usable Radio Frequency (RF) spectrum is assigned to either commercial operators or government organizations [6].

However, several parts of the radio spectrum have been preserved for licensed-free use. This is known as unlicensed spectrum. The unlicensed spectrum can be used by selected wireless technologies and it requires the compliance with predefined rules that ensure interference-free, fair and harmonious sharing of the available spectrum. Some of the most commonly used unlicensed frequencies are at $900MHz$, $2.4GHz$, $5GHz$, $24GHz$ and above $60GHz$. Several well-established wireless technologies operate in the unlicensed spectrum, such as IEEE 802.11x (Wi-Fi), Bluetooth, IEEE 802.15.4 (Zigbee), LORA, SIGFOX, etc. Today, Wi-Fi is the most commonly used technology in unlicensed spectrum (mainly in 2.4 and $5GHz$) as it can be incorporated in numerous devices, such as smartphones, personal computers, tablets, smart TVs, digital cameras and many more.

2.2 LTE in unlicensed spectrum

Over the last years, the licensed spectrum used by the mobile operators becomes very scarce and expensive. This has pushed the operators to search for solutions that allow them to cope with the ever-increasing load on their networks. Furthermore, due to the unprecedented increase of the wireless traffic, the mobile community started investigating solutions that can deal with massive amounts of traffic and can provide optimal spectrum use. Among other solutions (e.g. massive Multiple-Input Multiple-Output (MIMO), Carrier Aggregation, etc.), the operation of LTE in the unlicensed spectrum has attracted significant attention by the research community. As a result, several techniques have been proposed targeting to provide coexistence between LTE and other well-established technologies in unlicensed spectrum, such as Wi-Fi.

There are three predominant approaches for LTE operation in unlicensed spectrum depending on the regional regulations and the deployment scenario. In 2014, there was a first approach for LTE operation in unlicensed spectrum named LTE-Unlicensed (LTE-U). LTE-U is developed by the LTE-U Forum [7] to work with existing 3rd Generation Partnership Project (3GPP) Releases 10/11/12. It targets regions where a channel assessment before a transmission is not mandatory (e.g. USA). LTE-U Forum was created by Verizon in cooperation with Alcatel-Lucent, Ericsson, Qualcomm and Samsung. The aim of the forum is to create technical specifications that include minimum performance specifications for operating LTE-U base stations and consumer devices in unlicensed frequencies in the $5GHz$ band and coexistence specifications. The most prominent channel access mechanism for LTE-U is the Carrier Sense Adaptive Transmission (CSAT) [8] that has been proposed by Qualcomm. CSAT builds on elements of 3GPP Release 12 [9] and uses duty-cycle periods in order to give transmission opportunities (TXOP) to potential co-located networks. Hence, the time domain is divided in ON and OFF periods. During the ON periods, LTE can transmit in the unlicensed channel without previously assessing the medium for other ongoing transmission, while during the OFF periods, it remains silent. The duration of the ON and OFF periods is determined by the LTE base station, named evolved NodeB (eNB), based on the observed channel utilization (e.g. the estimated number of Wi-Fi Access Points (AP) or other technologies that operate in the same unlicensed channel).

In the beginning of 2016, 3GPP announced a standard that allows the operation of LTE in unlicensed spectrum as part of the 3GPP Release 13 [10]. The LTE operation in unlicensed spectrum standardized by 3GPP is known as LTE Licensed Assisted Access (LTE LAA). LTE LAA is intended to be a global standard as it requires a channel assessment procedure before a transmission in unlicensed spectrum, respecting this way the regional regulations worldwide. Initially and according to Release 13, only downlink (DL) LTE traffic can be transmitted in the unlicensed spectrum. In a later phase and according to Release 14 [11], it will be possible to offload both DL and uplink (UL) LTE traffic in the unlicensed channel. According to LTE LAA, an operator can deploy a secondary cell operating in the unlicensed spectrum in parallel to the licensed band that it owns. This way, it can opportunistically offload the LTE DL data traffic via the Physical DL Shared Channel (PDSCH) in the unlicensed channel. The LTE control signals and the UL traffic (according to Release 13) will be transmitted via the licensed anchor in order to guarantee an interference-free and on-time transmission.

Both LTE LAA and LTE-U require an operator that owns a licensed frequency band and opportunistically offloads LTE traffic in the unlicensed spectrum via a secondary cell. In order to decouple LTE from the operators and enable the LTE operation in unlicensed spectrum in standalone mode, leading wireless stakeholders formed the MulteFire Alliance [12]. MulteFire LTE builds on elements of LTE LAA and it is an ideal solution for organizations, mobile virtual network operators (MVNOs), Internet Service Providers (ISPs) or building owners for whom the licensed spectrum is scarce or unavailable.

Figure 2.2 gives an overview of the dominant approaches for the operation of LTE in the unlicensed spectrum.

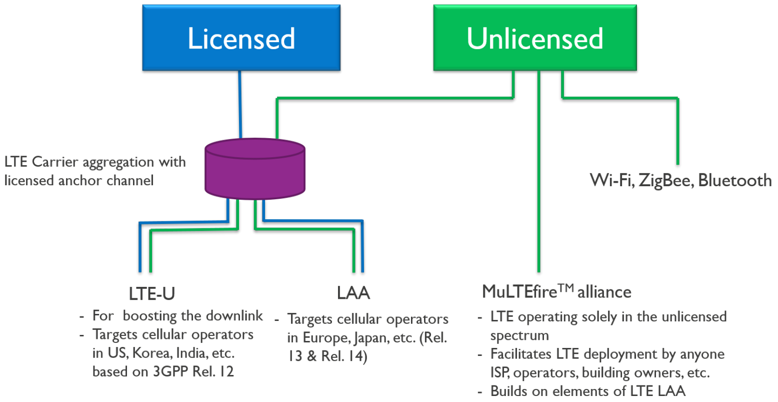

Figure 2.2: Overview of the dominant approaches for LTE operation in the unlicensed spectrum

LTE in unlicensed spectrum together with Wi-Fi are expected to play a key role in the new 5G era. Hence, it is assumed that the two technologies will operate harmoniously and fair next to each other. Nonetheless, they were not initially designed to coexist with each other. Their fundamental differences render the design of mechanisms that can enable fair coexistence or cooperation a very challenging procedure. The two following subsections briefly describe the two technologies, highlighting the characteristics that need to be taken into consideration during the design of such coexistence and cooperation mechanisms.

2.3 IEEE 802.11 (Wi-Fi)

IEEE 802.11 [13] is one of the most popular wireless technologies that is used to provide high-speed Internet and network connections in unlicensed spectrum. It is a set of Medium Access Control (MAC) and physical layer (PHY) specifications that instruct the implementation of wireless local area network (WLAN). IEEE 802.11 usually is deployed in the $2.4GHz$ UHF and $5GHz$ SHF radio bands.

The IEEE 802.11 standards are created and maintained by the Institute of Electrical and Electronics Engineers (IEEE) Local Area Network (LAN) / Metropolitan Area Network (MAN) Standards Committee (IEEE 802). In order to effectively manage the spectrum, regulatory bodies pose regional regulations that must be followed by every 802.11 compliant product within a respective region. The Federal Communications Commission (FCC) is the regulation body of the United States. In Europe, regulation is controlled at national level, following directives at European Commission level as defined by the Radio Spectrum Policy Programme (RSPP). IEEE 802.11 is an extensive and complicated standard. In order to avoid interoperability problems, the Wi-Fi Alliance [14] was formed by a group of major manufacturers. The Wi-Fi Alliance is a non-profit organization, which promotes Wi-Fi technology and certifies Wi-Fi products. The certification process is being done according to a defined test plan, based on IEEE 802.11 standards. However, within the test plan some features of IEEE 802.11 are not required for Wi-Fi certification, while there are requirements that are additional to the standard. Hence, Wi-Fi Alliance defines a subset of IEEE 802.11 features with some extensions. Today, due to misuse of the term and for marketing purposes, the name of the standard and the name of the certification are interchangeable. In the rest of the dissertation, the Wi-Fi term will be used to indicate wireless networks that are based on the IEEE 802.11 standards.

Wi-Fi uses Orthogonal Frequency Division Multiplexing (OFDM) digital modulation scheme that typically divides the spectrum into 64 OFDM subcarriers spanning $20MHz$ of bandwidth. From these subcarriers, 11 subcarriers are used as guard band between two adjacent channels and are inactive. The center subcarrier is called Direct Conversion (DC) subcarrier and is also inactive. From the remaining 52 subcarriers, 48 are assigned to data transmission and 4 are pilot subcarriers. The spacing between the subcarriers is $312.5kHz$. Thus, the actual occupied bandwidth is $16.6MHz$. Figure 2.3 [15] shows the 64 OFDM subcarriers, as they have been described above. All the data subcarriers use the same modulation type. According to the selected 802.11x standard, different modulation types are supported, such as Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), 16 Quadrature Amplitude Modulation (16QAM), 64QAM or 256QAM. The pilot subcarriers are always modulated using BPSK. Newer ver-

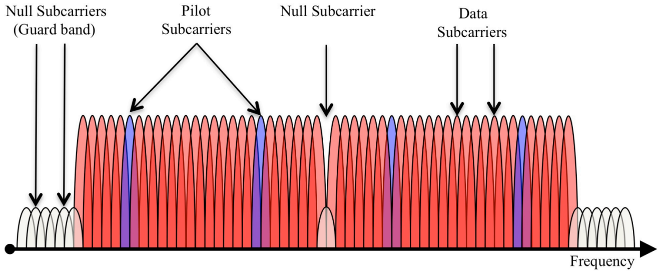

Figure 2.3: Wi-Fi OFDM subcarriers

sions of the IEEE 802.11 standard, such as 802.11n [16] and 802.11ac [17] can use wider bandwidth that can expand up to $40MHz$ and up to $160MHz$ respectively. Additionally, other versions such as IEEE 802.11ah [18] and 802.11af [19] use narrower bandwidth (e.g. $1MHz$, $2MHz$, $4MHz$, $8MHz$, $16MHz$ for 802.11ah and $6MHz$, $7MHz$ and $8MHz$ for 802.11af).

Wi-Fi uses the Distributed Coordinated Function (DCF) mechanism to access the medium, which is designed to be asynchronous and decentralized [13]. DCF employs Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) using exponential backoff. According to this method and as it is depicted in Figure 2.4, a Wi-Fi node has to determine if the channel is idle or busy before any transmission. This procedure is called Clear Channel Assessment (CCA) and is also known as Listen Before Talk (LBT). In the rest of the dissertation, the terms CCA and LBT will be used interchangeably.

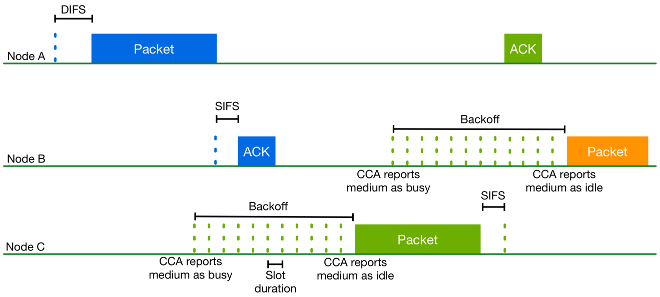

Figure 2.4: Wi-Fi CSMA/CA method

CCA consists of two functions named Carrier Sense (CS) and Energy Detection (ED). The CS function refers to the ability of the receiver to listen to the medium, to detect and successfully decode an incoming Wi-Fi preamble. If this is the case and the detected signal power is higher or equal to -82 dBm, then CCA reports the channel as busy for the timeslot that is indicated in the frame's Physical Layer Convergence Protocol (PLCP) header length field. This field contains either the time in μs that is required for the Medium Access Control (MAC) Protocol Data Unit (MPDU) payload transmission or the number of octets carried in the frame MPDU payload, which is used to compute the time required for the MPDU transmission. On the other hand, if the incoming signal cannot be decoded, the ED is used. The ED function refers to the ability of the receiver to detect the energy level in the operating channel based on non-Wi-Fi signals that are sensed in the same frequency band introducing interference or corrupted Wi-Fi transmissions that cannot be decoded. If the energy level is higher or at least equal to -62 dBm, then CCA reports the channel as busy. ED must sense the channel every time slot to estimate the energy level of the channel, as the length of time that the medium will be busy cannot be determined.

Every time a Wi-Fi node needs to transmit, it has to estimate the channel state for a DCF Inter-Frame Spacing (DIFS) interval. If the channel is idle, the node is allowed to transmit. Otherwise, if the channel is sensed as busy, the node must postpone its transmission and wait for a free DIFS, or if Quality of Service (QoS) is enabled, an Arbitration Inter-Frame Spacing (AIFS) period, plus a random backoff time to avoid packet collisions. The backoff counter indicates the number of slots during which the channel must be sensed as idle before a transmission can be performed. This number is uniformly selected within the Contention Window (CW) range. After a transmission, the node waits for an acknowledgement (ACK) that must be received during a Short Inter-Frame Space (SIFS) period. If the acknowledgement is not received during this interval, the node schedules a retransmission after a new exponential backoff period. In this case, the CW is doubled, until a maximum value (CW_{max}) is reached. This way, the probability of subsequent collisions is reduced. When the maximum number of retransmissions is reached, the packet is dropped. After a successful transmission, (the ACK has been received successfully) the value of the CW is re-initiated to its minimum value (CW_{min}).

In order to minimize potential collisions that may happen due to transmissions from hidden nodes, 802.11 standard provides an optional feature that is called Request to Send (RTS)/Clear to Send (CTS) [13]. The problem of hidden nodes can typically occur when the APs and the stations (STAs) are spread over an area and cannot identify the transmission of each other. As a result, the transmitted packets collide and several retransmissions occur. The RTS/CTS mechanism stipulates that a handshake is required between two nodes before they can start exchanging data. The protocol is illustrated in Figure 2.5. A node that has data to transmit sends an RTS frame. The RTS contains the duration of time that the node will reserve the medium. When the receiver receives an RTS, it replies with a CTS frame that also contains the reservation duration. This way, all the nodes in the proximity of the transmitter and the receiver can decode the RTS or CTS message and they

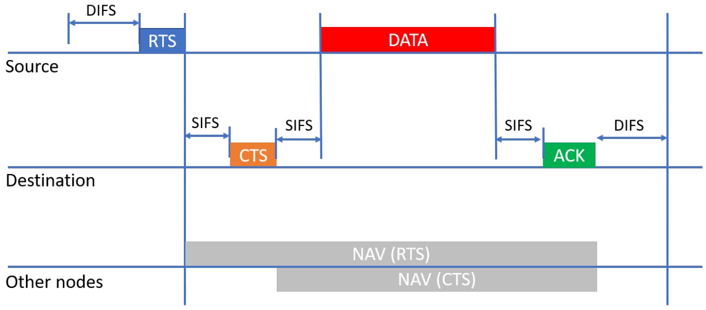

Figure 2.5: The RTS/CTS protocol

are informed to postpone their transmissions for the specified period of time. An important drawback of this mechanism is that the exchange of the RTS and CTS messages introduces extra overhead and delay to the network. Additionally, the RTS/CTS mechanism often fails to solve the hidden terminal problem (e.g. node beamforming in a specific direction, RTS/CTS message loss, etc.). Deep learning and technology recognition can play a significant role in solving the hidden terminal problem, as it is shown later in the dissertation.

2.4 LTE

LTE is a high-speed wireless cellular technology that increases the capacity and data-rate of the network using an advanced radio interface combined with a cutting-edge core network. By using innovative methods such as massive MIMO, Carrier Aggregation, advanced modulation schemes for both the DL and UL traffic and more, it manages the assigned spectrum in a very efficient way, approaching the Shannon limit [20].

The LTE standard is developed and maintained by 3GPP. 3GPP is a collaboration between groups of telecommunication standards associations, known as the Organizational Partners. The scope of 3GPP is to decide the standards of:

- GSM and the related 2G/2.5G standards (including GPRS and EDGE)
- UMTS and the related 3G standards (including HSPA)
- LTE and the related 4G standards (including LTE Advanced and LTE Advanced Pro)
- Next generation and the related 5G standards
- An evolved IP Multimedia Subsystem (IMS) developed in an access independent manner

The LTE standard was initially introduced in the Release 8 document series and until today (Release 14), it has been enhanced with several mechanisms that improve its performance and as a result the offered user experience.

LTE is a scheduled technology, meaning that the eNB is responsible to distribute the wireless resources in both frequency and time domain to the end devices named User Equipment (UE) that are attached to it. In the DL, Orthogonal Frequency-Division Multiple Access (OFDMA) is used as digital modulation scheme, which is a multi-user version of the OFDM scheme. In the UL, Single-Carrier Frequency-Division Multiple Access (SC-FDMA) digital modulation scheme is used. SC-FDMA can be interpreted as a linearly precoded OFDMA scheme. It uses an additional Discrete Fourier transformation processing step that precedes the conventional OFDMA processing. The advantage of SC-FDMA is that it solves a drawback of normal OFDM, namely the very high Peak to Average Power Ratio (PAPR). High PAPR requires expensive power amplifiers that have high requirements on linearity. This increases the cost of the end-devices and drains the battery faster.

LTE divides the time domain into frames of $10ms$ duration. One LTE frame, consists of 10 subframes, each one lasting for $1ms$. Each subframe consists of 2 slots of $0.5ms$ duration. Every slot contains 7 OFDM symbols when normal Cyclic Prefix (CP) is used and 6 OFDM symbols when extended CP is used. The frequency domain is divided into sub-carriers which are spaced at $15kHz$.

The smallest defined unit is a Resource Element (RE). It consists of one sub-carrier during one OFDM symbol interval. Each RE can be modulated using one of the 4 modulations used by LTE: QPSK, 16QAM, 64QAM and 256QAM that correspond to 2 bits, 4 bits, 6 bits and 8 bits of information respectively. Multiple REs aggregate into Resource Blocks (RB). A RB is the smallest unit of resources that can be allocated to a user. Each RB is 180 kHz wide in frequency domain and 1 slot long in time domain. Figure 2.6 [21] illustrates the LTE RB in both time and frequency domain, as described above. Figure 2.7 shows how traffic from multiple users is scheduled in time and frequency.

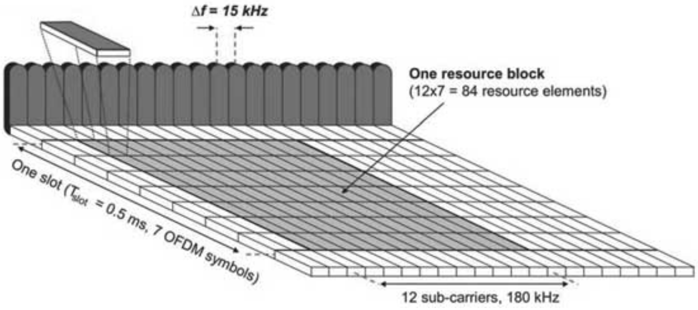

Figure 2.6: LTE Resource Block in time and frequency domain

The eNB schedules DL and UL data transmissions for multiple UE within one cell. This scheduling is performed with a period of $1ms$, meaning that every $1ms$ the assignment of resources per user can change.

LTE supports both Frequency Division Duplex (FDD) and Time Division Duplex (TDD). LTE FDD uses paired spectrum, meaning that the DL and the UL transmissions are performed in different frequencies. On the contrary, LTE TDD uses unpaired spectrum, meaning that the DL and UL transmissions are performed in the same frequency but in different subframes. 3GPP defines 7 different TDD configuration profiles. These profiles instruct which subframes will be used for DL and UL traffic. Even if there is no data traffic to be transmitted, LTE schedules

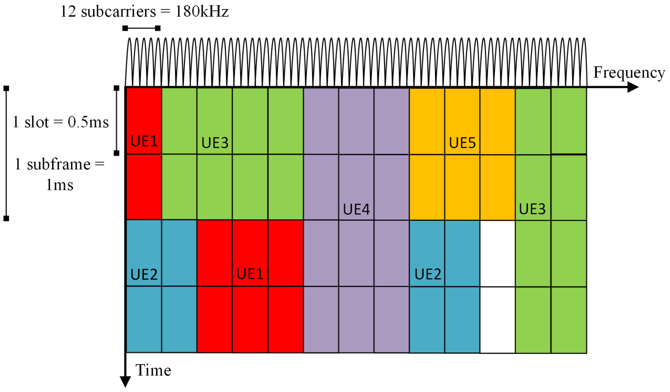

Figure 2.7: LTE time-frequency structure and user traffic scheduling. Each color represents a different UE that is scheduled by the Base Station

a plethora of signals that are mapped on each subframe [22]. Figure 2.8 [23], gives an overview of the LTE DL frame structure in FDD mode.

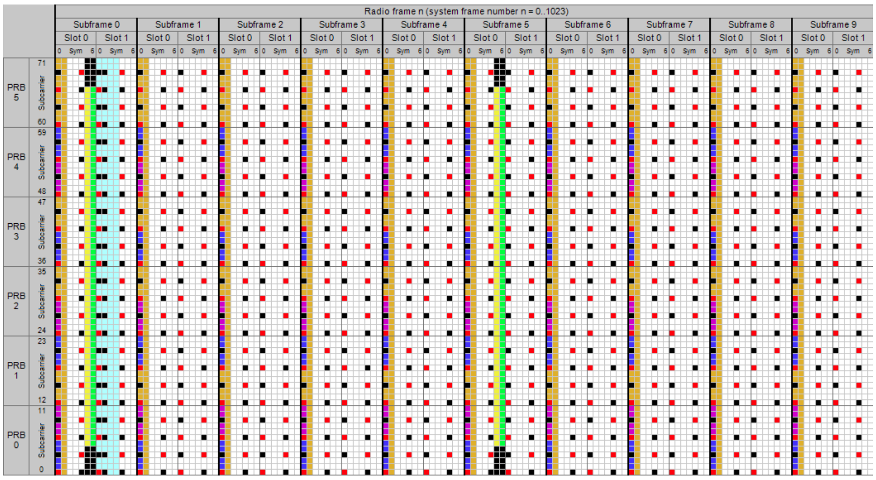

Figure 2.8: LTE FDD DL Resource Grid

The Primary Synchronization Signal (PSS) and the Secondary Synchronization Signals (SSS) are shown in green and in yellow color respectively. These signals are mapped on the PSCH (Primary Synchronization Channel) and SSCH (Secondary Synchronization Channel). They code the cell's physical cell ID, and their detection and decoding is essential for initial access of the UE when trying to connect to a cell and for time synchronization between the eNB and the UE. The PSS signal is transmitted on symbol 6 of slots 0 and 10 of each radio frame.

Similarly, SSS is transmitted on symbol 5 of slots 0 and 10 of each radio frame.

The Physical Broadcast Channel (PBCH) is shown in light blue color. PBCH broadcasts a limited number of parameters essential for initial access to the cell, such as DL system bandwidth and power settings. The reference signal of a cell, shown in red, is essential for channel estimation. Additionally, it assists the receiver to demodulate the received signal. In purple the Physical Hybrid Automatic Repeat reQuest (HARQ) Indicator Channel (PHICH) is shown. PHICH is used to carry the ACKs for UL data transfers.

The Physical Downlink Control Channel (PDCCH) is depicted by orange and is used to inform the UE about the scheduled resource allocation. It also carries other essential information such as the modulation, coding and HARQ information related to the data traffic. The Physical Control Format Indicator Channel (PCFICH) is shown in dark blue and it carries the Control Format Indicator (CFI). CFI instructs the number of symbols that can be used for control channels (PDCCH and PHICH). The blank symbols can be used for data transmission that is performed via the PDSCH. Finally, in black are depicted the symbols that are unused by the TX antenna port, or that are undefined for all the ports.

2.5 Coexistence of LTE and Wi-Fi in unlicensed spectrum

From the description of the key-elements of LTE and Wi-Fi, it becomes clear that these two technologies are not designed to coexist with each other. The coexistence issues are caused by fundamental differences in both the PHY and the MAC layer. Regarding the PHY, although similar modulation schemes are applied, PHY layer parameters are very different for both technologies: LTE uses long symbol duration of $71.4\mu s$ (including CP) and narrow subcarriers of $15kHz$, compared to Wi-Fi that uses short symbol duration of $4\mu s$ and wide subcarriers of $312.5kHz$. Figure 2.9 [24] illustrates the difference between LTE and Wi-Fi systems in both time and frequency domain.

Regarding the MAC design, the LTE scheduler is able to schedule simultaneously multiple users in both time and frequency domain, while Wi-Fi is packet-based and allocates all the subcarriers to a single user. Moreover, according to the CSMA/CA mechanism, every Wi-Fi node assesses the availability of the channel before a transmission in contrast to traditional LTE that assumes exclusive use of the assigned band. Figure 2.10 highlights the aforementioned differences on how LTE and Wi-Fi transmit in the wireless medium.

It becomes clear that the coexistence problem between LTE and Wi-Fi does not have a straightforward solution. Mechanisms that provide efficient and fair coexistence require careful design that takes into consideration the fundamental

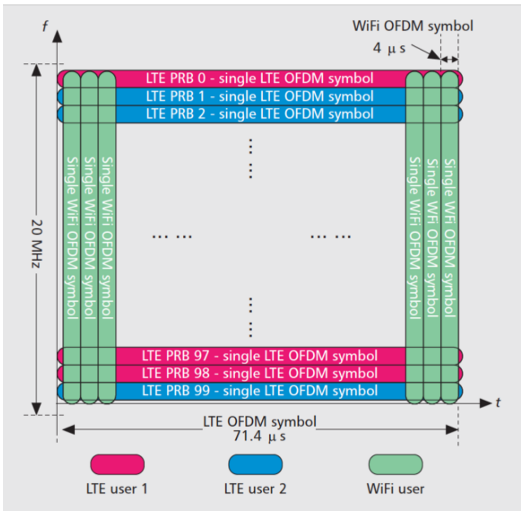

Figure 2.9: Comparison of LTE and Wi-Fi systems in both frequency and time domain

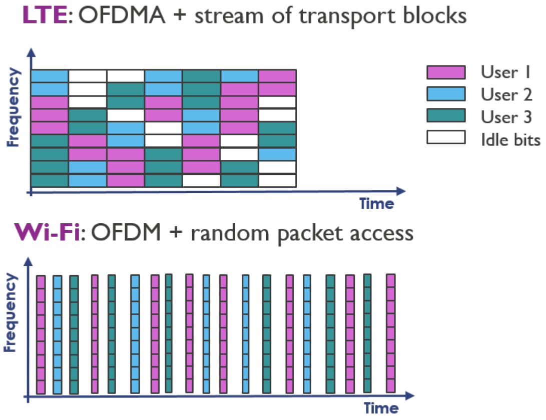

Figure 2.10: Comparison of transmissions between LTE and Wi-Fi systems

elements of each technology. Towards a solution that provides fair and harmonious coexistence there are several research challenges that must be overcome. These challenges are listed in the following chapter.

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3

Impact of LTE Operating in Unlicensed Spectrum on Wi-Fi Using Real Equipment

In the introductory chapter, it was emphasized that the study of the impact that traditional LTE can have on Wi-Fi when both networks operate next to each other is required to better understand the reasons that cause harmful coexistence between the two technologies. This study can assist significantly in designing coexistence and cooperation techniques that can enable fair spectrum sharing. This section focuses on the evaluation of the impact that LTE can have on Wi-Fi when no co-existence technique is implemented. For the purposes of this study, Commercial off-the-shelf (COTS) LTE and Wi-Fi equipment and open-source software implementations have been used in contrast to the related work that had focused only on mathematical analysis and simulations. This assisted in evaluating among others the impact of the LTE control signals on Wi-Fi, as well as the effect of different LTE transmission power levels. This chapter is a modified version of the original homonymous paper, which is published in IEEE Global Communications Conference (GLOBECOM).

⋆ ⋆ ⋆

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Abstract The proliferation of mobile devices and the exponential growth of data transmitted over the air pushed the wireless community to find solutions in order to increase network capacity and fully exploit the available spectrum. Recently, the 3rd Generation Partnership Project (3GPP) announced the operation of LTE in the unlicensed spectrum in order to offload the limited and expensive licensed spectrum. Concurrently, leading parties of the wireless community examine standalone operation of LTE in unlicensed spectrum. LTE was initially designed to operate in licensed spectrum and does not use any channel estimation mechanism to determine ongoing transmissions by other co-located networks. This introduces important coexistence challenges in unlicensed spectrum between LTE deployments and the current, well-established technologies, such as IEEE 802.11 (a.k.a. Wi-Fi). In this paper, we discuss the core differences between LTE and Wi-Fi, which lead to significant coexistence issues. We verify and showcase the problem by analyzing the performance degradation of Wi-Fi, when a traditional LTE network is co-located and operates in the same unlicensed frequency without any coexistence mechanism. The experiments are performed using open-source LTE and Wi-Fi implementations on real equipment in a fully controlled wireless environment. We conclude with showing the need for coexistence mechanisms, following the work that is being done within the standardization activities.

3.1 Introduction

Over the past few years, mobile devices such as smartphones, tablets, laptops and wearable technology have tremendously proliferated and changed the way people communicate, as they are online anytime and anywhere. According to Qualcomm, the already huge amount of traffic is expected to further increase by a factor of 1000 between 2010 and 2020 [1]. Hence, one can easily deduce that the wireless network capacity will soon become a bottleneck for this massive growth of wireless traffic.

LTE is a technology that approaches the Shannon limit and can assist significantly in solving the 1000x challenge. LTE is a scheduled technology that uses innovative methods such as Hybrid Automatic Repeat Request (HARQ) and carrier aggregation. These techniques render LTE capable to manage the available spectrum more efficiently than its predecessors and to achieve high data rates, low latency, QoS guarantees and fairness. However, the amount of available licensed spectrum is expensive and becomes limited, as the wireless technologies that use it, such as LTE, are consolidated and are intensively used by a growing amount of users.

Attempting to overcome these drawbacks, key players in the mobile wireless community have submitted proposals to the 3rd Generation Partnership Project (3GPP), which would allow LTE to operate in unlicensed spectrum bands. Within 3GPP activities on the LTE operation in unlicensed spectrum (also known as LAA Licensed-Assisted Access) have been started, as an enhancement towards LTE Release 13 [2]. LTE LAA will give the operators the possibility to use a secondary cell operating in the unlicensed spectrum alongside the primary cell operating in the licensed band that they own. There are two predominant proposals for LTE operation in unlicensed spectrum. According to the first one, a secondary cell on unlicensed spectrum will be used for supplemental downlink (DL) traffic only, while the uplink (UL) traffic will be transmitted on the operator's licensed spectrum. In the second proposal both supplemental DL and UL traffic will be transmitted via the cell operating in unlicensed spectrum. Additionally, big industry names founded the LTE-U Forum [3], which publishes specifications for minimum performance and coexistence mechanisms for evolved NodeB (eNB) and User Equipment (UE) operating in unlicensed spectrum, closely following the 3GPP specifications.

In parallel, many leading parties of the mobile world are doing preliminary steps to establish the LTE-U operation in standalone mode. To this end, they formed the MulteFire Alliance [4]. Their objective is to let LTE operate solely in unlicensed spectrum, so that it can be deployed by Internet service providers, cable companies, mobile operators, enterprises, building owners, etc.

The introduction of LTE into the unlicensed spectrum can significantly assist in dealing with the exponential data growth and moreover, it can solve the capacity problem that mobile operators face in order to provide the desired user experience. Furthermore, LTE in the unlicensed spectrum could considerably help in the increasingly important offloading of cellular networks through direct communications [5]. Nonetheless, LTE is a technology that is initially designed to operate in the licensed spectrum, assuming exclusive use of the assigned spectrum. It does not make use of a Listen Before Talk (LBT) mechanism in order to sense the medium and avoid collision with other ongoing transmissions from co-located networks. Hence, introducing LTE in unlicensed spectrum as it is, may have a detrimental impact on other co-located technologies that operate in the same bands, such as Wi-Fi [6].

In this paper, we analyze in depth and on real hardware the intuitive observation that LTE dominates Wi-Fi in a shared spectrum access mode. Until today, the literature lacks of a study that showcases the coexistence issues using real equipment. Initially and similar to the most technological breakthroughs the concept was studied using mathematical analysis and simulations. This paper targets to close this gap and presents the experimental verification of the impact of LTE on Wi-Fi using open-source LTE and Wi-Fi implementations on real equipment in a fully controlled wireless environment. During the experimentation we adopt the standalone operation of LTE in the unlicensed spectrum. We introduce LTE in unlicensed spectrum as it was originally designed without taking into account any coexistence mechanism and we examine the impact of LTE on Wi-Fi in terms of throughput and round trip latency. The paper highlights the need for coexistence mechanisms and aims to be used as a springboard for contribution to the discussion in 3GPP standardization about LTE operation in unlicensed spectrum by proposing potential improvements.

3.2 Related work

Although the LTE operation in unlicensed spectrum has only been announced recently, the problem of coexistence between LTE and Wi-Fi has already attracted many researchers and key players in wireless community, who study and evaluate the Wi-Fi performance degradation due to the presence of LTE. This performance evaluation is based mainly on mathematical models and simulations.

In [7] the authors investigate the deployment of LTE small cells instead of Wi-Fi by a mobile operator in a license-exempt band. Coexistence mechanisms with Wi-Fi are discussed, while UL performance analysis using simulation scenarios with both random and cluster placement is conducted. The results show that LTE can deliver significant capacity, even if it shares the spectrum with Wi-Fi networks.

A study that evaluates the performance of LTE and Wi-Fi in a shared frequency band using a simulation scenario is presented in [8]. As shown, LTE has a negative impact on Wi-Fi, especially in the case where many Wi-Fi users try to access the network simultaneously. By introducing a muting technique to LTE, the performance of Wi-Fi was increased, while LTE was still able to retain a fairly good performance.

In a similar way, the authors in [9] evaluate through simulations the performance impact of LTE and Wi-Fi when both operate in the same frequency. They propose a coexistence mechanism that exploits blank LTE subframes in order to give opportunity to Wi-Fi to transmit. They conclude that topology, as well as the number and order of the blank subframes lead to different performance results.

A framework in which a femtocell can access both licensed and unlicensed spectrum is proposed in [10]. In order to enable coexistence between LTE and Wi-Fi the authors propose an algorithm that enhances LTE with a channel sensing capability. The proposed framework is modelled and verified via simulations and the results showed a total throughput improvement of both cellular and non-cellular users.

An analytical model for evaluating the performance of co-located LTE and Wi-Fi networks is developed and used to obtain baseline performance measures in [11]. The results of the model have been partially validated via experimental evaluation using USRP platforms. Moreover, the authors propose an inter-network coordination with logically centralized radio resource management across LTE and Wi-Fi towards a fair coexistence.

Until today and except for the validation of the proposed interference characterization models in [11], the work that has been done studying the impact of LTE in unlicensed spectrum on Wi-Fi is focused on simulations or mathematical modelling. Hence, the literature lacks a study that investigates the coexistence results using real LTE and Wi-Fi equipment. This paper bridges this gap and presents the performance evaluation of Wi-Fi, when it is co-located with LTE operating in unlicensed spectrum, in a fully controlled environment using open-source equipment for both LTE and Wi-Fi networks.

3.3 LTE vs Wi-Fi

The analytical description of Wi-Fi [12] and LTE [13] technologies is given in the respective Sections 2.3 and 2.4 of Chapter 2. By this protocols' description it becomes clear that when a Wi-Fi network is co-located with an LTE network operating in unlicensed spectrum in the way it was originally designed, significant coexistence issues arise. The scheduler of LTE will schedule transmissions regardless the presence of Wi-Fi. This way it may directly interfere with potential Wi-Fi transmissions or act as hidden terminal. Especially in case of heavy loaded LTE network, it will monopolize the wireless resources resulting in the starvation of the Wi-Fi network.

3.4 Equipment and Experimentation Setup

For the purposes of this study an LTE network with open-source equipment for eNodeB and UE [14] has been deployed and configured to operate in the unlicensed spectrum. Simultaneously, a Wi-Fi network operates in the same frequency band. The experiments were conducted on the LTE and Wi-Fi infrastructure of the W-iLab2 testbed at iMinds [15].

The LTE network consists of 2 software-defined radio (SDR) EXPRESS-MIMO2 (EXMIMO2) boards [16] that run the OpenAirInterface (OAI) software [17]. The attached radio daughter board covers a large part of the RF spectrum (250MHz to 3.8GHz) allowing the definition of channels in the unlicensed spectrum. On top of these boards the OAI software is running. OAI aims to provide an open-source solution for both the LTE Evolved Packet Core (EPC) network and the LTE access-network (EUTRAN) of 3GPP cellular systems. In our setup, one EXMIMO2 board has been configured to operate as eNB and the other as UE.

In order to enable LTE operation in unlicensed spectrum, a new band was defined in the OAI software, which uses the same center frequency as Wi-Fi channel 6 (2.437GHz). The width of the band is 5MHz, as currently OAI permits LTE operation only in a 5MHz bandwidth. OAI supports both Frequency Division Duplex (FDD) and Time Division Duplex (TDD). In this study we focus on TDD mode, in order to investigate the interaction between Wi-Fi and LTE operating in a single frequency band for both DL and UL traffic. 3GPP defines 7 different DL/UL configuration profiles for the LTE TDD mode. Table 3.1 presents the 7 different TDD configurations, where "D" and "U" symbolize a DL and an UL subframe respectively, and "S" symbolizes a special subframe.

Table 3.1: DL/UL TDD Configurations

DL/UL Config.	**DL to UL switch periodicity (ms)**	**Subframe number**									
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0	5	D	S	U	U	U	D	S	U	U	U
1	5	D	S	U	U	D	D	S	U	U	D
2	5	D	S	U	D	D	D	S	U	D	D
3	10	D	S	U	U	U	D	D	D	D	D
4	10	D	S	U	U	D	D	D	D	D	D
5	10	D	S	U	D	D	D	D	D	D	D
6	5	D	S	U	U	U	D	S	U	U	D

There are 9 different configurations for special subframe as can be seen in Table 3.2. Each special subframe is divided into three parts: DwPTS (DL Pilot Time Slot), GP (Guard Period) and UpPTS (UL Pilot Time Slot). Different configurations allocate different number of Orthogonal Frequency Division Multiplexing (OFDM) symbols in each part. The GP is a transition gap between the DL and the UL. DwPTS is considered as a normal DL subframe and carries reference signals and control information, such as PSS (Primary Synchronization Signal). It can also carry data, when a configuration with a sufficient amount of OFDM symbols is selected. The UpPTS is primarily used for SRS (Sounding Reference Signals) transmission from the UE.

For the purpose of this study, the system has been configured to use TDD configuration profile "3", providing a good proportion between the DL and UL timeslots in an LTE frame, and configuration "0" for the special subframe.

The Wi-Fi network consists of 2 nodes configured in infrastructure mode. One node operates as Access Point (AP) and the other as station (STA). Both the AP and the station use a Qualcomm Atheros AR928X wireless network adapter and the ath9k driver [18]. The Wi-Fi network operates in channel 6 of the 2.4 GHz band, operating in 802.11g mode.

In order to have a clean environment without any interference from other net-

Table 3.2: Special Subframe Configurations (OFDM symbols) for normal and extended cyclic prefix (CP)

Config.	**Normal CP**			**Extended CP**		
	DwPTS	**GP**	**UpPTS**	**DwPTS**	**GP**	**UpPTS**
0	3	10	1	3	8	1
1	9	4	1	8	3	1
2	10	3	1	9	2	1
3	11	2	1	10	1	1
4	12	1	1	3	7	2
5	3	9	2	8	2	2
6	9	3	2	9	1	2
7	10	2	2	-	-	-
8	11	1	2	-	-	-

works, both the LTE and the Wi-Fi equipment are placed in fully RF shielded boxes. These boxes are interconnected with each other using COAX cables through combiners/splitters and programmable attenuators. Both the LTE and the Wi-Fi networks are configured in SISO (Single Input Single Output) mode. Hence, only one antenna port in both the transmitter and the receiver has been used.

3.5 Experimentation Results

The purpose of this paper is to evaluate to which degree the performance of Wi-Fi is affected by a co-located LTE network transmitting in an overlapping frequency band in the way it was originally designed to operate, hence without any coexistence mechanism. Both the achieved Wi-Fi throughput and Wi-Fi round trip latency are adopted as key performance indicators. UDP traffic was sent for both the LTE and the Wi-Fi networks. The datagram size has been set to 1470 bytes and no RTS/CTS mechanism has been used by the Wi-Fi network.

When the Wi-Fi network does not experience any interference from LTE, the station is able to achieve an average DL throughput of 28.10Mbps. In the remainder of the paper we refer to this throughput without LTE interference as TREF. By monitoring the WLAN interface of the station, it has been noticed that in order to reach this throughput, the network used a high physical rate of 54Mbps. This is to be expected, as the RF shielded boxes and the interconnection via COAX cables offer an ideal, interference-free environment, where Wi-Fi can use a high Modulation and Coding Scheme (MCS) profile to transmit.

Figure 3.1a presents an LTE frame of 10ms in a time vs power measurement. This LTE frame includes only control signals in the DL, as there is no UE attached and consequently there is no traffic in the Physical DL Shared Channel (PDSCH) nor in the Physical UL Shared Channel (PUSCH). This frame clearly shows the “3”

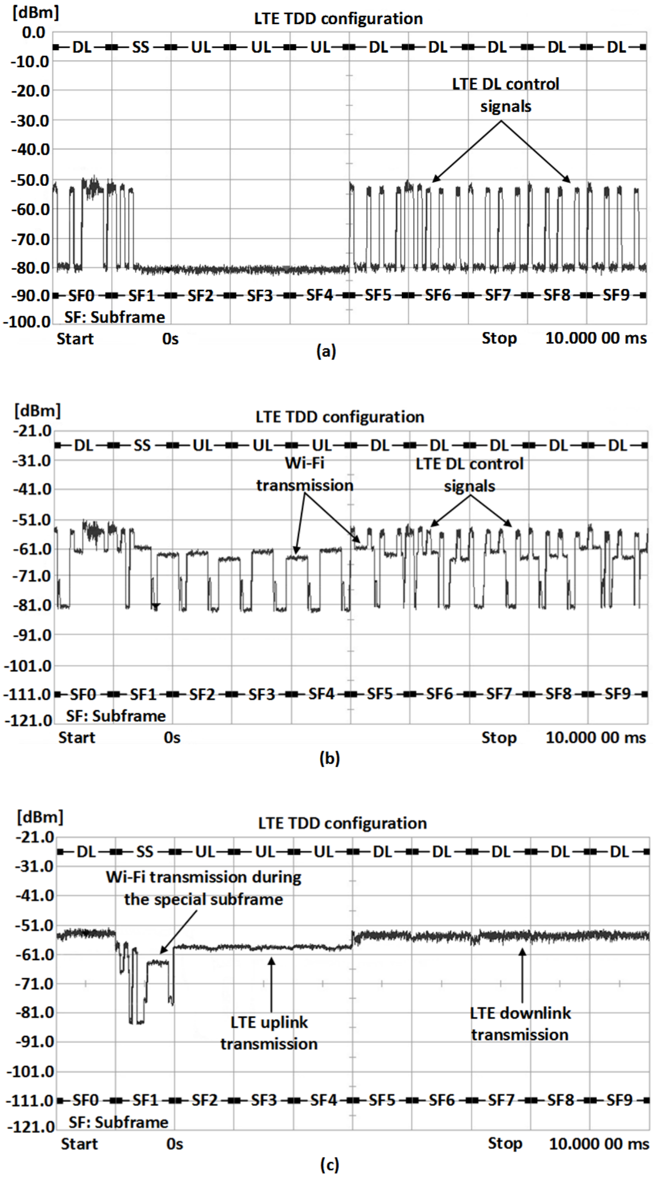

Figure 3.1: Time vs. power analysis showing: a) LTE DL control signal transmissions b) Wi-Fi transmission opportunities between the LTE DL control signals c) Simultaneous LTE and Wi-Fi traffic.

TDD DL/UL configuration profile (Table 3.1) that has been used, which consists of a DL subframe followed by a special subframe, 3 UL subframes and 5 DL subframes. As it can be observed, the control signals from the eNB are fairly sparse, offering many potential time slots to a co-located Wi-Fi network to transmit. This can be verified by Figure 3.1b, which presents a Wi-Fi transmission alongside the eNB DL control signalling. It can be seen that Wi-Fi finds many opportunities to transmit covering the gaps between the LTE control signals. Figure 3.1c depicts the time vs power signal measurement of simultaneous traffic by LTE and Wi-Fi with a duration of 10ms. This period of time equals to the duration of an LTE frame, in which LTE and Wi-Fi compete to access the medium. As can be seen, LTE sends DL or UL traffic during almost the whole time frame. Wi-Fi only has an opportunity to transmit during the special subframe, when LTE remains silent due to the guard period, between DL and UL transmissions.

One would expect that, since Wi-Fi has opportunities to transmit only during the GP, the throughput would be proportional to the duration of the GP, which depends on the special subframe configuration profile. Nonetheless, in the examined setup the LTE uses a 5MHz bandwidth, while the Wi-Fi network operates in a 20MHz bandwidth. This means that LTE overlaps only with 25% of the Wi-Fi channel. Figure 3.2 illustrates a 25MHz spectrum analysis during LTE and Wi-Fi transmissions. If the LTE signal is not strong enough to surpass the Energy Detection (ED) threshold of the Clear Channel Assessment (CCA) mechanism, or when LTE operates as hidden terminal, then Wi-Fi will not be able to sense the medium as busy and will attempt to transmit. This will cause LTE to interfere with Wi-Fi within the overlapping subcarriers. However, the OFDM modulation scheme that Wi-Fi uses in combination with the coding rate and error correction mechanisms render it capable to receive and decode data even though a part of the 20MHz spectrum is occupied. Despite the interference, a part of the transmitted

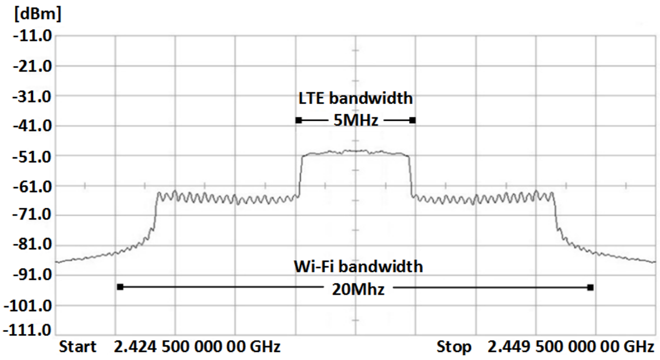

Figure 3.2: The LTE and the Wi-Fi signal in frequency vs power analysis.

packets can be successfully decoded at the receiver. Clearly, if the LTE bandwidth is higher, the amount of data that Wi-Fi would be able to decode will be lower. In case the detected LTE signal power is higher than the ED threshold, the Wi-Fi backoff mechanism is triggered.

In this study, we examine three different levels of LTE signal power in both the eNB and the UE. These power levels represent the different degrees that Wi-Fi can be affected by LTE operating in unlicensed spectrum in the way that it was originally designed.

The first one is symbolized as L1 and is not strong enough to surpass the ED threshold of the Wi-Fi CCA mechanism. Hence, Wi-Fi cannot sense the medium as busy and as a result LTE causes interference to ongoing Wi-Fi transmissions.

The second LTE power level is symbolized as L2. L2 is higher than the ED threshold of the Wi-Fi CCA and is able to force Wi-Fi to backoff every time there is an LTE transmission in the DL and in the UL.

The third examined LTE power level is symbolized as L3. At this level or above, LTE signals cause the surpassing of the sensitivity threshold at the Wi-Fi network. On modern Wi-Fi adapters the sensitivity threshold determines the lowest signal level for which the station remains associated with the current AP. If the signal level goes below this threshold the card disassociates and searches for a better AP.

Table 3.3 presents the different experimental scenarios that have been investigated and shows the measured Wi-Fi performance in terms of throughput and latency. Each scenario is defined by the type of LTE traffic together with the LTE signal power level. Figure 3.3 summarizes the average measured values of Wi-Fi throughput and round trip latency for each scenario.

Table 3.3: Experimental Scenarios

Scenario ID	**LTE signal power level**	**Type of LTE traffic**	**Wi-Fi throughput value**	**Wi-Fi latency value**
1	-	none	28.1 Mbps	1.37 ms
2	L1	DL CTRL signal	16.81 Mbps	1.6 ms
3	L1	DL and UL traffic	7.53 Mbps	3.01 ms
4	L2	DL CTRL signal	6.22 Mbps	2.98 ms
5	L2	DL and UL traffic	1.84 Mbps	5.92 ms
6	L3	DL CTRL signal	disassociated	disassociated
7	L3	DL and UL traffic	disassociated	disassociated

The results show that even when LTE transmits only DL control signals, it is already able to cause severe interference to Wi-Fi, reducing its throughput drastically (Scenario 2 and 4). When LTE uses the L1 signal power, then its control

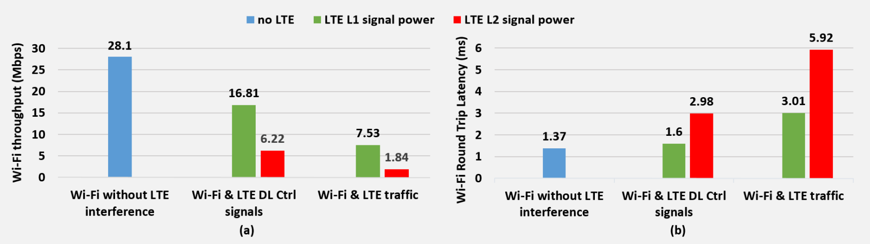

Figure 3.3: Wi-Fi average throughput and round trip latency in standalone operation and under different levels of LTE interference.

signals interfere with the Wi-Fi and decrease its throughput to 16.81Mbps. This means that the Wi-Fi throughput has been reduced by 40.08% compared to TREF. In the second case, when the L2 LTE signal power is used, the average Wi-Fi throughput reduction is even higher reaching 77.86% compared to TREF.

When LTE transmits continuously in both the DL and UL, the throughput of Wi-Fi is decreased even more (Scenario 3 and 5). In the first case, in which LTE transmits using the L1 signal power, Wi-Fi does not sense the channel as busy. As Wi-Fi transmits concurrently with LTE an amount of useful information is lost due to the symbol mapping on the Wi-Fi subcarriers that face interference from LTE. If the receiver is not able to recover the lost information this will result to packet loss and retransmissions. As the experiment results show, the LTE interference is strong enough to reduce the average Wi-Fi throughput by 73.20% compared to TREF. On the other hand, when LTE uses the L2 signal power, then Wi-Fi senses the medium as busy during DL and UL LTE transmissions. Thus, Wi-Fi is able to transmit only during the GP of the special subframe, in which LTE remains silent due to the switch between DL and UL. The results show that the average Wi-Fi throughput in this case is limited to 1.84Mbps and equals to a degradation of 93.45%.

By the time LTE starts transmitting using the L3 power level, it surpasses the sensitivity threshold of the Wi-Fi station. Hence, the Wi-Fi station disassociates from the AP and starts looking for another AP with better operating conditions (stronger signal, lower interference). In case there is no other AP that can serve the station, it remains disassociated. This way LTE completely eliminates Wi-Fi.

In terms of latency, the Wi-Fi network experiences an average round trip latency of 1.37ms, when there is no LTE activity (Scenario 1). By the time LTE is active the latency of Wi-Fi is significantly increased. When LTE uses the L1 signal power, then the presence of the LTE control signals in the DL raises the Wi-Fi round trip latency to 1.6ms. This raise becomes even higher when LTE transmits continuously in both the DL and the UL and reaches the average value of 3.01ms. Furthermore, when the L2 signal power is used the LTE control signals in the DL increase the Wi-Fi latency by 117.5%. The impact of concurrent DL and UL LTE traffic is even higher leading to an average latency increment by a factor of 3.32.

3.6 Conclusions and Future Work

This study has shown how the performance of a Wi-Fi transmission is affected by LTE using real hardware, when both technologies are co-located in unlicensed spectrum without any coexistence technique deployed. For the purpose of this study, we have used real LTE and Wi-Fi equipment in a fully controlled wireless environment. The results show that the Wi-Fi performance is severely affected by LTE in terms of achieved throughput and latency. We show that even if LTE does not send data traffic, the throughput of Wi-Fi is reduced significantly due to the LTE control signals. Furthermore, this reduction becomes even more pronounced when LTE transmits arbitrarily in both PDSCH and PUSCH channels. Three different levels of LTE signal have been examined, each one representing the different level of impact that LTE may have on Wi-Fi. As the results showed even if the LTE signalling does not surpass the ED threshold of CCA, the Wi-Fi transmissions experience significant interference from LTE. In case the LTE signal is higher than the ED threshold, it forces Wi-Fi to backoff and under concurrent DL and UL transmission it gives opportunities to the medium only during the GP period of the TDD configuration. Finally, when the LTE transmission power exceeds the Wi-Fi sensitivity threshold, it forces the Wi-Fi station to disassociate from the AP, eliminating this way the Wi-Fi network. If there are many UEs in the LTE network, the resources would be divided to the UEs by the LTE scheduler. In a heavy loaded network, the impact on Wi-Fi is expected to be at least the same as the examined case in this paper, where there is continuously DL traffic to one UE. In case there are multiple Wi-Fi STA, then the impact on Wi-Fi is expected to be higher as more STA would compete during the idle slots. The verification of these assumptions has been left for future work.

From the results above, it is clear that the design and implementation of coexistence mechanisms are needed in order to achieve a harmonized coexistence between LTE and Wi-Fi in the unlicensed spectrum. The main reason that LTE interferes with Wi-Fi is because it does not sense the medium before a transmission. By enhancing LTE with a carrier sensing mechanism it would be able to avoid interference with other ongoing transmissions and backoff or move to another channel using a DFS (Dynamic Frequency Selection) technique. 3GPP has already started working on the definition of standards towards the enhancement of LTE with CCA. Another dominant solution is the scheduling of blank subframes in LTE. This solution is applicable to regions where no CCA requirements are defined. During these subframes LTE would remain silent, giving Wi-Fi the opportunity to transmit. In this case, we could consider similar techniques used in enhanced Inter-Cell Interference Coordination (eICIC), where LTE subframes in a certain cell are reserved for neighbouring cells. This solution requires a careful and sophisticated selection of the amount of blank subframes, in order to keep a balance between sufficient Wi-Fi transmission opportunities and LTE performance. In the near future, we are planning to further contribute to the ongoing research and standardization towards the compelling coexistence between LTE and Wi-Fi and propose potential improvements.

Acknowledgment

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4

Cooperation Techniques between LTE in Unlicensed Spectrum and Wi-Fi towards Fair Spectral Efficiency

After investigating the impact of traditional LTE on Wi-Fi in Chapter 3, we know the reasons that result in harmful coexistence between the two technologies. This chapter investigates different cooperation techniques that can improve the performance of both networks and offer fair spectrum sharing. To this end, (i) a taxonomy of techniques that can be applied between co-located LTE and Wi-Fi networks is presented, (ii) the state if the art is studied extensively followed by an overview of the regional requirements for the unlicensed spectrum, (iii) several cooperation schemes that can enhance the performance of co-located LTE and Wi-Fi networks are proposed and compared in terms of expected synchronization requirements, their complexity and their expected performance. This chapter is a modified version of the original homonymous article, which is published in the MDPI Sensors Journal.

⋆ ⋆ ⋆

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Abstract On the road towards 5G, a proliferation of Heterogeneous Networks (HetNets) is expected. Sensor networks are of great importance in this new wireless era, as they allow interaction with the environment. Additionally, the establishment of the Internet of Things (IoT) has incredibly increased the number of interconnected devices and consequently the already massive wirelessly transmitted traffic. The exponential growth of wireless traffic is pushing the wireless community to investigate solutions that maximally exploit the available spectrum. Recently, 3rd Generation Partnership Project (3GPP) announced standards that permit the operation of Long Term Evolution (LTE) in the unlicensed spectrum in addition to the exclusive use of the licensed spectrum owned by a mobile operator. Alternatively, leading wireless technology developers examine standalone LTE operation in the unlicensed spectrum without any involvement of a mobile operator. In this article, we present a classification of different techniques that can be applied on co-located LTE and Wi-Fi networks. Up to today, Wi-Fi is the most widely-used wireless technology in the unlicensed spectrum. A review of the current state of the art further reveals the lack of cooperation schemes among co-located networks that can lead to more optimal usage of the available spectrum. This article fills this gap in the literature by conceptually describing different classes of cooperation between LTE and Wi-Fi. For each class, we provide a detailed presentation of possible cooperation techniques that can provide spectral efficiency in a fair manner.

4.1 Introduction

Over the past few years, the technological growth combined with the proliferation of wireless devices such as sensors, smartphones, laptops and wearable technology has changed the way that information is exchanged. The number of interconnected devices and the number of Heterogeneous Networks (HetNets) increase rapidly. The development and the consolidation of wireless sensor networks has further contributed to the increase of the wireless traffic, as often they consist of hundreds to thousands of wireless sensor nodes. The first-generation Internet has evolved into the Internet of Everything, where massive amounts of information are exchanged between devices using different types of mainstream and well-established wireless technologies such as LTE, Wi-Fi, IEEE 802.15.4 and Bluetooth. Recently, the sub-gigahertz bands have been extensively exploited by wireless technologies that offer wide ranging communications, such as LORA, SIGFOX and 802.11ah. Moreover, high frequency bands such as mmWave are also being used for multi-gigabit speeds (IEEE 802.11ad). According to Qualcomm, the amount of wireless traffic is expected to further increase by a factor of 1000 by 2020 [1]. Additionally, Cisco's latest forecast expects that the traffic from wireless and mobile devices will exceed the overall wired traffic by 2019 [2]. Based on these predictions, the wireless network capacity will soon become a bottleneck for the massive growth of wireless traffic.

The 5G community has already started investigating solutions that can tackle the $1000\times$ challenge. These solutions include among others, enhanced massive Multiple-Input Multiple-Output (MIMO), carrier aggregation, higher-order modulation schemes such as 64-Quadrature Amplitude Modulation (QAM) or 256-QAM, cloud computing services and advanced network architecture modifications. At the same time, the adoption of LTE from different applications gains ground, as it is a technology that approaches the Shannon limit and can contribute significantly to solving the network capacity challenge.

Recently, key players of the mobile world have proposed standards to the 3rd Generation Partnership Project (3GPP), which allow LTE operation in the unlicensed spectrum. To this end, 3GPP announced the operation of LTE Licensed-Assisted Access (LTE LAA) [3], as an enhancement within 3GPP LTE Release 13. LTE LAA will allow operators to use a secondary cell operating in the unlicensed spectrum, alongside the primary cell operating in the licensed band they own. The carrier aggregation that has been introduced in 3GPP LTE Release 10 [4] will be used to enable this feature.

On the other hand, leading wireless stakeholders other than mobile operators are taking the first steps towards exploitation of LTE in the unlicensed spectrum as a standalone wireless solution complementary to Wi-Fi. To this end, they formed the MulteFire Alliance [5]. Their target is to decouple LTE from the operators, so it can be deployed by Internet service providers (ISPs) enterprises, building owners, cable companies, etc.

Figure 4.1 indicates how LTE in the unlicensed spectrum could be deployed next to the current wireless infrastructure, where an LTE-U small cell could be either an LTE LAA small cell, controlled by a mobile operator, or a small cell operating solely in the unlicensed spectrum without mobile operator control.

LTE is a technology that has been initially designed to operate in the licensed spectrum. Hence, it assumes that it can exclusively use the whole assigned spectrum, and therefore, it does not incorporate any techniques for harmonious coexistence with other possible co-located technologies. It is clear that introducing LTE in the unlicensed spectrum as is will cause significant coexistence issues with other well-established technologies such as Wi-Fi, IEEE 802.15.4 or Bluetooth. This means that LTE will have a negative impact on the performance of traditional unlicensed technologies in terms of throughput, latency and other Quality of Service (QoS) guarantees [6], affecting their applications such as wireless (sensor) networks, Device-to-Device (D2D) and Machine-to-Machine (M2M) communications. To this end, research has focused on the design and evaluation of coexistence techniques for LTE, in order to enable fair spectrum sharing with other technologies operating in the unlicensed spectrum, and in particular with Wi-Fi. On the

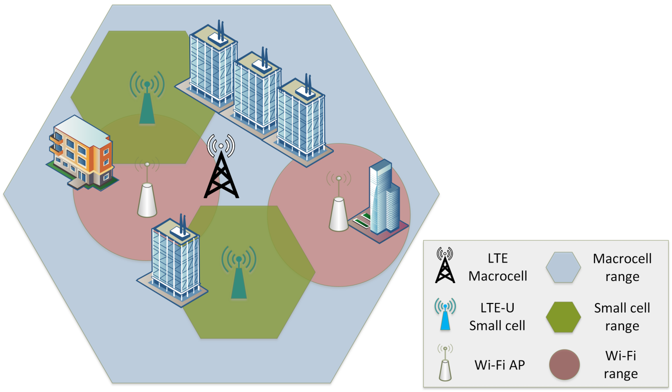

Figure 4.1: Deployment of LTE in the unlicensed spectrum next to the current infrastructure.

other hand, much less attention has been paid to cooperation techniques between the two technologies. The networks that participate in a cooperation scheme are able to exchange information directly or indirectly (via a third-party entity) in order to improve the efficiency of spectrum usage in a fair way.

In this article, we distinguish two different classes of cooperation between LTE and Wi-Fi, and for each class, we propose and analyze potential cooperation techniques that can be applied. For each cooperation technique, we analyze the advantages and disadvantages regarding the design and deployment complexity, the flexibility and the efficiency they could offer. The proposed techniques can contribute to the open discussion regarding the standardization process of the LTE operation in the unlicensed spectrum. The main contribution of this work is summarized as follows:

- Classification of techniques that can be applied on co-located LTE and Wi-Fi networks
- Detailed analysis of the current state of the art regarding LTE in the unlicensed spectrum and Wi-Fi covering:
  - Analysis of the standard LTE and Wi-Fi protocols
  - The regional regulations for the unlicensed spectrum
  - The impact of LTE on Wi-Fi without applying any coexistence technique
  - The current approaches for coexistence between LTE and Wi-Fi
- Analysis of the different concepts of cooperation between LTE and Wi-Fi and potential techniques that can be applied for realizing each concept

- Comparison and feasibility of the different presented concepts

The remainder of the article is organized as follows. Section 4.2 presents a classification of the techniques that can be applied when LTE and Wi-Fi networks are co-located and operate in the same (unlicensed) frequency band. Section 4.3 discusses the current state of the art for LTE operation in the unlicensed spectrum. Next, in Section 4.4, we analytically present the concept of direct cooperation between LTE and Wi-Fi via in-band energy level patterns and showcase possible cooperation techniques. Section 4.5 presents the concept of cooperation between LTE and Wi-Fi using indirect communication through a third-party entity and describes possible cooperation techniques. In Section 4.6, we compare the proposed concepts and techniques. Finally, in Section 4.7, we conclude the paper and discuss plans for future work.

4.2 Taxonomy of Techniques for Co-Located LTE and Wi-Fi Networks

This section presents a taxonomy of techniques that can be applied when an LTE network is co-located with a Wi-Fi network and both networks operate in the same frequency band. This taxonomy is presented in Figure 4.2. As can be seen, co-located LTE and Wi-Fi networks can be classified into three big categories depending on the techniques that are applied between them.

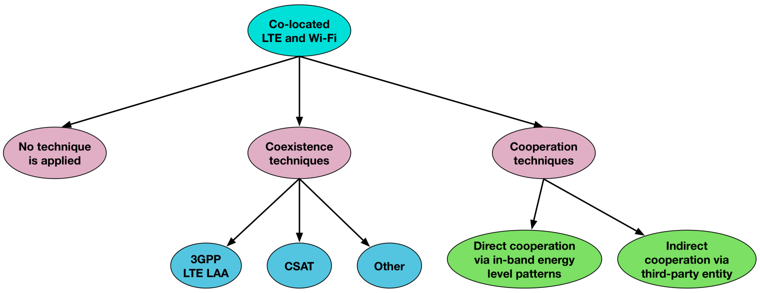

Figure 4.2: Taxonomy of the techniques that can be applied to co-located LTE and Wi-Fi networks.

In the first category, the networks operate next to each other in the way they were initially designed, without any technique that improves the symbiosis between them. This is the worst type of co-location scenario as LTE transmissions result in a severe impact on Wi-Fi [7].

The other two categories classify two co-located networks based on whether the applied technique aims to provide coexistence or cooperation between the networks. Coexistence and cooperation are two terms that differ significantly. With the term coexistence, we refer to methodologies that enable peaceful operation of a wireless technology next to another. The technologies must respect each other, as well as the regional regulations and seek equal opportunities to access the wireless medium, under the condition that there is no exchange of any information between different technologies. On the other hand, the cooperation term refers to methodologies that seek collaboration among the technologies towards harmonious coexistence and optimal spectrum usage by exchanging information. The cooperation between different technologies is in line with the 5G vision, where all of the available wireless technologies will act towards enhancing the user experience.

As can be seen from Figure 4.2, coexistence techniques include the 3GPP LTE LAA mechanism and other techniques that are described later in Section 4.3. Although coexistence techniques between LTE operating in the unlicensed spectrum and Wi-Fi have been studied widely, the literature, to the best of our knowledge, consists of only a limited number of studies focusing on cooperation techniques among the two technologies. This paper targets covering this gap by classifying the possible cooperation schemes and proposing potential techniques that can be applied in each category. The different cooperation techniques can be classified into the following two big categories, based on the way that the participating networks communicate with each other:

- Direct cooperation via in-band energy level patterns
- Indirect cooperation via a third-party entity

The first category includes techniques that make use of one or multiple in-band energy patterns in order to perform technology identification, inform about their actions or achieve synchronization between multiple networks that participate in the cooperation scheme.

The second category refers to the ability for different wireless technologies to exchange messages via a third-party entity, in order to maintain synchronization and explicitly describe their characteristics and requirements.

4.3 State of the Art

4.3.1 LTE vs Wi-Fi

The mechanisms that Wi-Fi [8] and LTE [9] use to transmit in the way that they were initially designed is analytically described respectively in Sections 2.3 and 2.4 of Chapter 2. The analysis of the core differences among these mechanisms can give us the insight to understand in depth the reasons why LTE cannot operate next to Wi-Fi without appropriate coexistence and cooperation mechanisms. Moreover, it will be used as a basis for the subsequent description of the different cooperation protocols.

4.3.2 Regional Regulations

In order to enable fair coexistence among LTE and Wi-Fi, research has been focusing on designing coexistence techniques that will allow LTE to operate in the unlicensed spectrum, respecting the different regional regulations. Concurrently, these techniques aim to fairly share the medium with other well-established technologies like Wi-Fi. For instance, the European Telecommunications Standards Institute (ETSI) defines requirements [10] that should be fulfilled by each technology that operates in the unlicensed spectrum. These requirements among others include:

- Clear Channel Assessment (CCA) before transmission together with timing requirements for each CCA phase
- Maximum antenna gain
- Transmission power limitations

Table 4.1 summarizes the regional regulations that must be obeyed by a technology that operates in the unlicensed spectrum. In the table, DFS stands for Dynamic Frequency Selection and TPC stands for Transmit Power Control.

4.3.3 Impact of LTE Operating in the Unlicensed Spectrum on Wi-Fi

The previous section has described the different operational methods for LTE and Wi-Fi. It is clear that introducing LTE into the unlicensed spectrum, in the way it was originally designed, will have a significant impact on the performance (throughput, latency, packet loss, spectral efficiency) of a co-located Wi-Fi network. As LTE can schedule traffic without sensing the medium for ongoing transmissions, it can interfere with Wi-Fi within the overlapping spectrum. Hence, the CCA mechanism of Wi-Fi, and more specifically the Energy Detection (ED) function, will force Wi-Fi to backoff. This impact can become even higher by consecutive LTE transmissions. Then, LTE will either seriously degrade the signal quality of Wi-Fi due to collisions (if the LTE signal power is below the ED threshold, but still high enough to interfere with the Wi-Fi transmissions), or lead to Wi-Fi starvation, as it will be forced to backoff continuously.

Several studies have evaluated the impact of traditional LTE on Wi-Fi, when both technologies operate in the same frequency band without any coexistence mechanism being applied. In our previous work [7], we studied the impact of

Table 4.1: Regional requirements for the unlicensed spectrum.

Frequency/ Region		2.4 GHz	5150-5250 MHz	5250-5350 MHz	5470-5725 MHz	5725-5850 MHz
EU	Coexistence	Listen Before Talk, Maximum Transmit (TX) power, Emission mask				
	Protect incumbent	-	Indoor	Indoor/Outdoor DFS/TPC	Indoor/Outdoor DFS/TPC	-
USA	Coexistence	FCC Part 15.247, 15.401-407, Maximum TX power, Emission mask				
	Protect incumbent	-	Indoor	Indoor/Outdoor DFS/TPC	Indoor/Outdoor DFS/TPC	Indoor/Outdoor
China	Coexistence	Maximum TX power, Emission mask				
	Protect incumbent	-	Indoor	Indoor DFS/TPC	-	Indoor/Outdoor
Japan	Coexistence	Listen Before Talk, Maximum burst length (4ms), Maximum TX power, Maximum antenna gain, Emission mask				
	Protect incumbent	-	Indoor	Indoor DFS/TPC	Indoor/Outdoor DFS/TPC	-
Korea	Coexistence	Maximum TX power, Maximum antenna gain, Emission mask				
	Protect incumbent	-	Indoor	Indoor/Outdoor DFS/TPC	Indoor/Outdoor DFS/TPC (5470-5650)	Indoor/Outdoor

LTE operating in the unlicensed spectrum on Wi-Fi using Off The Shelf (OTS) hardware equipment [11]. The experiments were performed on the LTE and Wi-Fi infrastructure of the W-iLab2 testbed at imec [12]. Three different levels of LTE signal have been examined, representing different possible levels of LTE impact on Wi-Fi. The results show that the Wi-Fi performance, in terms of throughput and latency, can be significantly affected by LTE.

Other approaches evaluate the Wi-Fi performance degradation based on simulations and mathematical models. In [13, 14], the authors evaluate the performance of both LTE and Wi-Fi when both technologies operate in a shared band. All studies come to the same conclusion, namely that LTE causes a serious impact on Wi-Fi, when both operate in the same band without any coexistence mechanism among them and no medium sensing mechanism enabled at the LTE side.

4.3.4 Proposed Coexistence and Coordination Techniques

4.3.4.1 LTE LAA Approach

Towards a coexistence technique that respects the regional regulations, 3GPP announced the LTE LAA standards in Release 13, including the description of a Listen Before Talk (LBT) procedure (also known as CCA) [15]. Initially, LTE LAA is scheduled to operate within the 5-GHz unlicensed spectrum and for DL traffic only, but in a later phase, it is expected to be extended to the 2.4-GHz unlicensed band, as well as for both DL and UL traffic. Initially, an evolved NodeB (eNB) will be able to activate and deactivate a secondary cell operating in the unlicensed spectrum. Through this cell, only data traffic (via the Physical Downlink Shared Channel (PDSCH)) can be sent, while the LTE control signals and the UL traffic (Physical Uplink Shared Channel (PUSCH)) will be transmitted via the licensed anchor. The eNB must perform the LBT procedure and sense the channel prior to a transmission in the unlicensed spectrum. When the channel is sensed as busy, the eNB must defer its transmission by performing an exponential backoff. If the channel is sensed to be idle, it performs a transmission burst with a duration from 2 ms–10 ms, depending on the channel access priority class. The authors in [16] analytically describe the LTE LAA procedure. They provide an overview of the LAA mechanism including the motivation and use cases where it can be applied. Additionally, they present a coexistence evaluation methodology and results, which have been contributed by 3GPP. Figure 4.3 shows the LTE LAA and Wi-Fi coexistence in the same channel in the unlicensed spectrum.

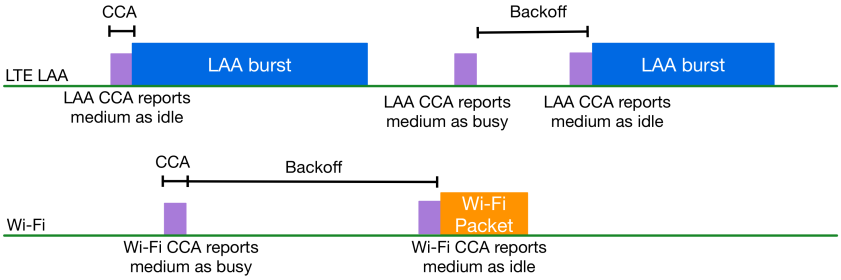

Figure 4.3: LTE Licensed-Assisted Access (LAA) and Wi-Fi coexistence.

4.3.4.2 LTE CSAT Approach

In regions such as the U.S., China and South Korea, where an LBT procedure is not required by the local regulations, different types of coexistence techniques can be applied. Carrier Sensing Adaptive Transmission (CSAT) [17], proposed by Qualcomm, is a technique that can enable coexistence among LTE and Wi-Fi based on minor modifications of the 3GPP LTE Release 10/11/12 Carrier Aggregation protocols [4]. CSAT introduces the use of duty cycle periods and divides the time into LTE “ON” and LTE “OFF” slots. During the LTE “OFF” period, also known as the “mute” period, LTE remains silent, giving the opportunity to other coexistent networks, such as Wi-Fi, to transmit. During the LTE “ON” period, LTE accesses the channel without sensing it before a transmission. Moreover, CSAT allows short transmission gaps during the LTE “ON” period to allow for latency sensitive applications, such as VoIP in co-located networks. In CSAT, the eNB senses the medium for a time period ranging from tens of ms up to 100 ms and according to the observed channel utilization (based on the estimated number of Wi-Fi Access Points (APs)) defines the duration of the LTE “ON” and LTE “OFF” periods [17]. Figure 4.4 depicts the CSAT duty cycle periods.

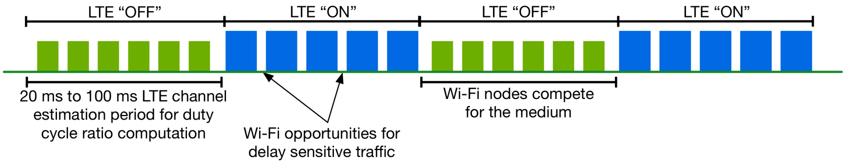

Figure 4.4: Carrier Sensing Adaptive Transmission (CSAT) duty cycle periods.

4.3.4.3 Other Related Work

Coexistence between LTE and Wi-Fi in the unlicensed spectrum has attracted the attention of the mobile and the research community. There are several proposed mechanisms, trying to achieve fair coexistence between the two technologies. These mechanisms are evaluated on the success of providing the desired fairness.

In [18], the authors discuss a preliminary design of a semi-distributed LTE in the unlicensed spectrum scheme, where the eNB senses the carrier before a transmission in a similar way to Wi-Fi. They use a method that exploits the LTE Almost Blank Subframes (ABS). The ABS were initially designed to enhance Inter-Cell Interference Coordination (eICIC) as part of 3GPP LTE Release 10 [19]. The proposed method evaluates different duty cycles, different distances between an eNB and an AP and different numbers of cells. Different ABS patterns are also studied.

In [20], the authors propose an LTE subframe design consisting of three phases named the data transmission phase, the mute phase and the sensing and reservation phase. Based on this subframe design, they proposed three schemes to enable coexistence among LTE and Wi-Fi. The first scheme assumes a fixed mute duration. The second scheme uses a randomized mute duration. The third scheme introduces a random backoff counter during the mute period. The three proposed schemes are evaluated through simulations. The results show that the scheme that uses a random mute duration offers better overall throughput performance, while the scheme that uses a random backoff counter results in smaller throughput difference between LTE and Wi-Fi.

The authors in [21] describe an analytical framework for interference characterization of Wi-Fi and LTE. Initially, a first model is described for single LTE and single Wi-Fi AP separated by a specific distance. The results show that Wi-Fi performance is significantly decreased compared to LTE for which the degradation is minimal. They observe that the conventional perception of the inverse proportion of throughput to inter-AP distance is not valid for LTE-Wi-Fi co-channel deployment. A second model with many LTE and Wi-Fi systems is also described. The results show that the overall system throughput first increases and then decreases with growing density. Finally, in order to increase the individual Radio Access Technology (RAT) and system throughput, random channel assignment, intra- and inter-RAT channel coordination are considered. In the intra- and inter-RAT channel coordination schemes, the channel is allocated at an AP as a graph multi-coloring problem. The results show 3.5–$5\times$ gains in system capacity. In this technique, the networks do not exchange specific information in order to optimize the offered QoS, but different frequencies are assigned to them in order to avoid overlapping frequencies between co-located networks.

In [22, 23], the authors use Q-Learning techniques to achieve the desired coexistence. In [22], they propose a Q-Learning-based dynamic duty cycle selection mechanism for configuring LTE transmission gaps. LTE LAA and Wi-Fi performance using a fixed transmission gap is evaluated and then compared with the proposed Q-Learning mechanism. Simulation results show that the proposed scheme enhances the overall capacity performance. The authors in [23] propose a Q-Learning mechanism for advanced learning of the activity within the unlicensed band resulting in efficient coexistence between LTE LAA and Wi-Fi. As a next step, the coexistence is further enhanced through a double Q-Learning method that takes into account both discontinuous transmission and transmit power control of LTE to improve both LTE and Wi-Fi performance.

Coexistence of LTE and Wi-Fi when LTE uses an LBT procedure is studied in [24–27]. The authors in [24] propose an adaptive LBT protocol for LTE LAA. This protocol enhances the coexistence with Wi-Fi and increases the overall system performance. The protocol consists of two different mechanisms named on-off adaptation for channel occupancy time and short-long adaptation for idle time. The first mechanism is responsible for adapting the channel occupancy time of LTE based on the load of the network, while the second one adapts the idle period based on the Contention Window (CW) duration of Wi-Fi. The authors in [25] propose an LBT mechanism for LTE LAA that aims to share the medium in a fair way towards the increase of the overall system performance. This work includes both a mathematical analysis and a validation via simulation of the proposed LBT scheme. The results show that a proper selection of LAA channel occupancy and the backoff counter can increase the performance of Wi-Fi. In [26], the authors study the coexistence among LTE LAA and Wi-Fi using the LBT category four-channel access scheme. The behavior of LAA eNB is modeled as a Markov chain, and the obtained throughput is adopted as the performance metric. The proposed LBT scheme uses an adaptive CW size for LTE LAA. According to the results, the proposed scheme outperforms the fixed CW size. In [27], the authors examine how LTE cells in the unlicensed spectrum from different operators can adjust their CW in order to tune the LBT algorithm and provide coexistence both with Wi-Fi and among themselves in an altruistic way. The interaction of LTE cells in the unlicensed spectrum is studied using a coalition formation game framework, which is based on the Shapley value.

In [28], the authors present an analytical model for evaluating the performance of coexistence between LTE and Wi-Fi. This model has been used to obtain baseline performance measures. The results of the model have been partially validated via experimental evaluation using Universal Software Radio Peripheral (USRP) platforms. Moreover, the authors propose an inter-network coordination with logically centralized radio resource management across LTE and Wi-Fi as a solution to improve coexistence.

The authors in [29] propose two non-coordinated and two coordinated network management approaches to enable coexistence. Regarding the non-coordinated techniques, the first one proposes eNB to perform LBT on different channels and to switch to a different channel after a transmission, while the second proposes LTE to offer transmission opportunities of variable duration to Wi-Fi after a transmission based on the occupancy of the medium. Concerning the coordinated methodologies, the first one proposes a Network Function Virtualization (NFV) interconnection to combine the Wi-Fi network and the service provider of LTE in the unlicensed spectrum. This way, channel selection and seamless transfer of resources between the two technologies can be enabled, using the in-the-cloud control of distributed APs. The second method proposes the management of coexistence using the X2 interface among the eNBs. The eNBs can exchange information and schedule ABS in different subframes, thus giving more opportunities to any Wi-Fi network that is located potentially within their proximity. In the aforementioned schemes, the different RATs are under the control of the same mobile operator. The coordination between the wireless technologies targets the enhancement of the overall QoS that the operator offers (e.g., perform load balancing via frequency coordination).

Finally, the authors in [30] provide a detailed survey of the coexistence of LTE and Wi-Fi on 5 GHz with the corresponding deployment scenarios. They provide a detailed description of the coexistence-related features of LTE and Wi-Fi, the coexistence challenges, the differences in performance between the two different technologies and co-channel interference. They extensively discuss the proposed coexistence mechanisms between LTE and Wi-Fi in the current literature. Furthermore, the survey discusses the concept of the scenario-oriented coexistence, in which coexistence-related problems are solved according to different deployment scenarios.

Although the coexistence between LTE operating in the unlicensed spectrum and Wi-Fi is being investigated extensively, little attention is given to studies that investigate cooperation scenarios among the two technologies. As has been discussed in Section 4.2, in this paper, we distinguish two different types of cooperation between LTE in the unlicensed spectrum and Wi-Fi. Furthermore, for each solution, we propose and describe different techniques that can lead to efficient and fair spectrum use.

4.4 Direct Cooperation via In-Band Energy Level Patterns

4.4.1 Introduction

This section describes cooperation techniques between co-located LTE and Wi-Fi networks that operate in the same frequency band, using in-band pattern recognition in order to enhance the spectral efficiency of the coexisting networks. A cooperation scheme that uses in-band pattern recognition can be applied, when the co-located networks do not have the ability to communicate between each other (e.g., via a coordinator) in order explicitly to express their requirements. The in-band pattern recognition methodology allows direct cooperation between different wireless technologies, as it can be used for technology identification and inter-RAT synchronization. Moreover, a wireless technology can use one or more in-band special patterns in order to inform other technologies about different actions that it performs. Upon the recognition of such a pattern, a wireless network will be able to adapt its behavior towards an increased performance (e.g., higher throughput) and more advanced spectrum usage. Figure 4.5 depicts an example of an in-band pattern recognition. In this example, a predefined energy level pattern is transmitted by the LTE eNB. This pattern is used for the identification of the LTE network by a Wi-Fi AP.

For a technique of such a nature, the complexity of the design and the implementation is relatively low, as only small modifications of the current protocols of each wireless technology are required in order to transmit and interpret such energy level patterns. Nevertheless, the low complexity of the methodologies implies also a limited flexibility, meaning that upon sensing a co-located wireless technology, each network takes some predefined actions that can contribute to more efficient spectrum sharing and/or performs readjustment and tuning of existing coexistence

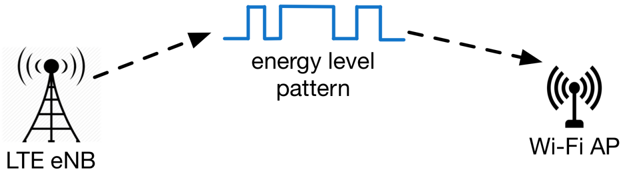

Figure 4.5: LTE identification via the predefined energy level pattern.

techniques.

4.4.2 Enhanced CSAT

One negative aspect of the CSAT algorithm, as described in Section 4.3.4.2, is that it requires a very long sensing period ranging from 20 ms up to 100 ms, in order to observe the activity in the medium and decide the LTE "ON" and LTE "OFF" periods. Furthermore, at the end of an LTE "OFF" period or at the end of a Wi-Fi opportunity slot during the LTE "ON" period, LTE starts transmitting without sensing the medium for ongoing Wi-Fi transmissions. This results in several collisions among LTE and Wi-Fi. These drawbacks can be eliminated by the use of an energy level pattern periodically transmitted by the eNB. Such a pattern can be sensed by Wi-Fi and other LTE networks in order to achieve inter- and intra-technology synchronization and to adjust their behavior.

In the proposed methodology, we define three different energy level patterns that can be used for different purposes. These patterns are defined as follows:

- Synchronization pattern that enables inter- and intra-technology synchronization and that is transmitted by the first activated network
- LTE identification pattern that is transmitted by the eNB of a newly-activated LTE network in order to inform the rest of the networks about its presence
- Wi-Fi identification pattern that is transmitted by the AP of a newly-activated Wi-Fi network in order to inform the rest of the networks about its presence

Additionally, we define a new time frame as is depicted in Figure 4.6. This time frame starts with a period T_{SYNC} dedicated to transmission and reception of the synchronization pattern. Then, the main part of the frame is called T_{TX} and is divided into slots for LTE and Wi-Fi traffic. The last part of the frame is called T_{IDENT}, and it is used for LTE and Wi-Fi pattern transmission, in order to identify any new networks and adjust the LTE and Wi-Fi slots for the next time frame. Initially, when a new network is activated, it must sense the medium for a period of time equal to a frame in order to discover potential synchronization patterns. If such a pattern does not exist, then the network starts periodically transmitting a synchronization pattern signal to enable inter- and intra-technology synchronization. On the other hand, if the new network senses a synchronization pattern, then it does not initialize a periodic synchronization pattern signal transmission, but it keeps sensing the medium to identify the next synchronization pattern that is expected at the beginning of the next frame. At the moment that two sequentially synchronization patterns are sensed, then the new network can be in synchronization with the rest of the networks. The length of a frame can be stable over time or can vary based on the number of cooperating networks and the amount of transmitted traffic. In the case that a variable frame size is used, then the new network must sense the medium to discover a potential synchronization pattern for a time period that is equal to the maximum frame length.

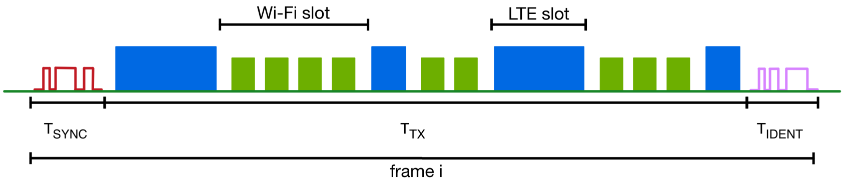

Figure 4.6: Enhanced CSAT time frame.

From the moment that the newly-activated network is in synchronization with the rest of the networks, it must transmit a corresponding LTE or Wi-Fi identification pattern during the next T_{IDENT} period. This way, the rest of the networks will be notified for the new LTE or Wi-Fi network. The newly-activated network can identify the LTE and Wi-Fi slots that have already been created by sensing the medium during a T_{TX} period. The network that is in charge of transmitting the synchronization pattern transmits its identification pattern only after it senses the first identification pattern from another network during the same T_{IDENT} period. If an LTE or Wi-Fi identification pattern is sensed during the T_{IDENT}, then the LTE and Wi-Fi slots during the T_{TX} period are readjusted. This readjustment is done based on the number and the type of the co-located networks. The creation of the new slots will be decided based on the same predefined mechanisms for both LTE and Wi-Fi networks. Moreover, the length of the LTE and Wi-Fi slots will be decided based on the common scheduling mechanism that is used by LTE and Wi-Fi. Furthermore, during a time slot, the eNBs and the APs will measure the channel utilization in order to further adapt the slots for the next frame.

As we mentioned above, the T_{TX} phase is divided into Wi-Fi and LTE slots. During the Wi-Fi slots, the different nodes will be able to compete for the medium using the traditional Carrier Sensing Multiple Access with Collision Avoidance

(CSMA/CA) method, as has been described in Section 2.3. On the other hand, during an LTE slot, one or more eNBs can schedule transmissions to their attached UEs. Up to today, much work has been done towards interference mitigation between different eNBs, known as eICIC, which was initially introduced in 3GPP LTE Release 10 [19]. Additionally, eNBs could sense the medium before a transmission to further reduce interference. Figure 4.7 shows the flowchart of the algorithm described above.

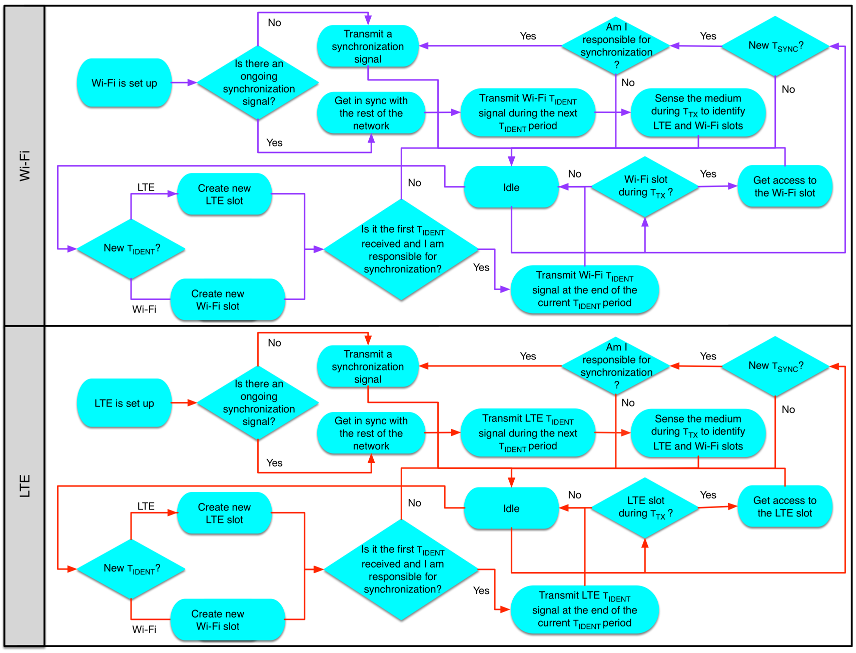

Figure 4.7: Enhanced CSAT flowchart.

From the description of the method above it is clear that such a cooperation method, for all the advantages that it offers such as intra-technology synchronization, interference management and indirect technology recognition, also has some aspects that require further investigation. For instance, mechanisms should be included that are capable of merging separate co-located networks that have been set up using this cooperation technique or mechanisms that can cope with potentially lost special patterns. This is outside the scope of this paper.

The described technique requires small changes for both LTE eNB and Wi-Fi AP. Firstly, both wireless technologies must be able to transmit, detect and recognize the different energy level patterns that have been described above for synchronization and scheduling purposes. Moreover, the Medium Access Control (MAC) protocols of LTE and Wi-Fi need to be modified in order to create and access the LTE and Wi-Fi slots based on the received T_{IDENT}.

4.4.3 Enhanced LTE LAA

Cooperation techniques among LTE and Wi-Fi can further enhance the current coexistence techniques such as LTE LAA, providing improved use of the available spectrum towards an enhanced user experience.

3GPP has introduced four different channel access priority classes for DL LTE LAA. Table 4.2 shows the different priority classes, where the smaller the number of the class, the higher the priority. This table is defined in the 3GPP specifications describing the channel access procedure for LTE LAA [15]. In this table, m_p is the number of slots in a defer period, while CW_{min} and CW_{max} are the respective minimum and maximum values of the CW size. As can be seen, each priority class uses different $T_{m\,cot,p}$, which refers to the maximum channel occupancy time for priority class p. For the priority Classes 3 and 4, $T_{m\,cot,p}$ is 10 ms if the absence of any other co-located technology sharing the same spectrum band can be guaranteed on a long-term basis. In a different case, it is limited to 8 ms. According to the LTE LAA standards, an eNB cannot continuously transmit in the unlicensed spectrum for a period longer than $T_{m\,cot,p}$. On the other hand, when frame aggregation is not used, Wi-Fi transmits only one packet when it gains access to the medium performing CCA. A Wi-Fi packet transmission typically lasts a few hundreds of μs. It is clear that the ratio among LTE and Wi-Fi channel occupancy is not balanced.

Table 4.2: LTE LAA channel access priority classes.

Channel access priority class (p)	m_p	$CW_{min,p}$	$CW_{max,p}$	$T_{m\,cot,p}$	Allowed CW_p sizes
1	1	3	7	2 ms	3,7
2	1	7	15	3 ms	7,15
3	3	15	63	8 or 10 ms	15,31,63
4	7	15	1023	8 or 10 ms	15,31,63,127,255,511,1023

To render LTE LAA fairer for Wi-Fi, we propose a scheme according to which LTE will transmit using an adaptable maximum channel occupancy time. Moreover, a variable mute period of LTE-LAA after a transmission can also be introduced, as is depicted in Figure 4.8, in order to avoid consecutive LTE burst transmissions. The proposed scheme can be further enhanced by introducing cooperation using in-band energy level patterns. In this case, a Wi-Fi or an LTE network can announce its presence by transmitting a corresponding identification special energy pattern. This way, an LTE network will be informed about the presence of other LTE or Wi-Fi networks. LTE can use this information to select and adjust both the burst duration and the mute period.

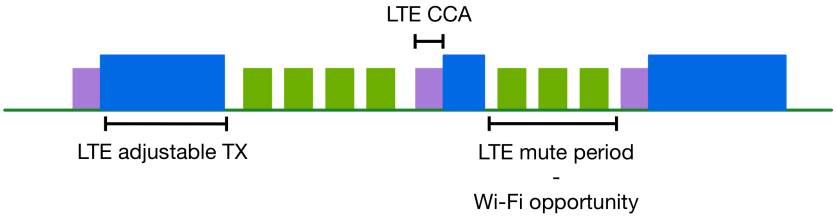

Figure 4.8: LTE adjustable channel occupancy time and mute period.

The decision of the channel occupancy time and the length of the mute period will be made based on a combination of parameters. One important parameter is the number of present Wi-Fi and LTE networks, which have been identified by an identification special energy pattern. This information can assist LTE to keep a balance of channel occupancy in time. Another important parameter that can further enhance this balance is the channel utilization during the silent periods of LTE, meaning the backoff period and the LTE mute period. The LTE must continuously sense the medium to identify the amount of transmitted traffic. Then, it can decide the maximum transmit duration and the length of the mute period. The type of traffic, such as delay-sensitive traffic, can be part of the decision. However, delay-sensitive traffic can be transmitted via the licensed anchor if the unlicensed channel utilization is high. Hence, a quiet channel will result in a short or zero mute period and a high channel occupancy time. On the other hand, an active channel will result in a higher mute period and a shorter occupancy time. It is clear that the algorithm that controls the LTE transmission duration and the LTE mute period is critical. As a first approach, the LTE network can use a slow start type of algorithm. According to such an algorithm, LTE will access the medium for a satisfying portion of time if no other technology is present for a long time. By the time it detects inter-technology coexistence, it will reset back to a minimum value. Then, it will try to find a new balance towards a harmonious coexistence with Wi-Fi.

The method described above requires small modifications to the LAA LTE standards to allow variable mute and channel occupancy periods based on the decisions that the LTE scheduler will make, as well as transmission, reception and interpretation of the special energy patterns.

4.4.4 Advanced Frequency Selection

The aforementioned cooperation techniques can be further enhanced by an advanced frequency selection mechanism. Wi-Fi systems already support DFS (Dynamic Frequency Selection) that can be used by adjacent and non-centrally coordinated APs to avoid interference. DFS is mandatory in the 5250–5350-MHz and 5470–5725-MHz Unlicensed National Information Infrastructure (U-NII) bands of unlicensed spectrum for radar avoidance [31]. Within 3GPP, it has been agreed that a frequency selection functionality is an implementation issue and will not be part of the LTE specifications [32]. An advanced frequency selection mechanism will increase LTE fairness in the unlicensed spectrum and render it compliant with the regional regulations.

In the case of the cooperation technique that is described in Section 4.4.2, an eNB can sense the activity on different channels in the unlicensed spectrum. If an idle channel is available, it can decide to perform a new frequency selection and either start the transmission of the periodic synchronization pattern, if there is not already one, or it can be synchronized with another existing network that already periodically transmits a synchronization pattern. In order to avoid radio link failure among the eNB and the UEs that are attached to it, the eNB must notify the UEs about the new frequency that will be used, so they can perform the transition synchronously.

The same frequency selection procedure can be adopted regarding the enhanced LTE LAA technique that is described in Section 4.4.3. An eNB operating in LTE LAA can sense multiple unlicensed channels in order to move to a less busy one. Similar to the first case, the eNB must notify the attached UEs about the new frequency and initiate the transition progress.

4.4.5 Inter-RAT TDMA

The RTS (Request to Send)/CTS (Clear to Send) method has been introduced in the 802.11 standard as an optional feature to control the access to the medium [33]. If RTS/CTS is enabled, then a Wi-Fi node will not transmit until it completes an RTS/CTS handshake. According to this handshake, before a data transmission, a node first transmits an RTS frame to the destination indicating how long the transmission will last. The receiver should reply with a CTS message after a Short Inter-Frame Space (SIFS) period. CTS contains a time value that informs other nodes to postpone their transmission during the length of this value. Using the in-band pattern recognition methodology, an inter-RAT RTS/CTS method can be developed among LTE and Wi-Fi, as is depicted in Figure 4.9. Using such a method, the co-located wireless technologies can reserve the medium for a maximum time duration. This way, they can operate in an inter-technology Time Division Multiple Access (TDMA) way.

In this method, we introduce two different energy level patterns that can be used to reserve and release the medium. These patterns are defined as follows:

- Reservation energy level pattern. This pattern is used by a wireless network to inform other co-located networks that it will reserve the medium for a period of time smaller or equal to a maximum transmission duration.

- Release energy level pattern. This pattern is used by a wireless network to inform other co-located networks that the medium has been released.

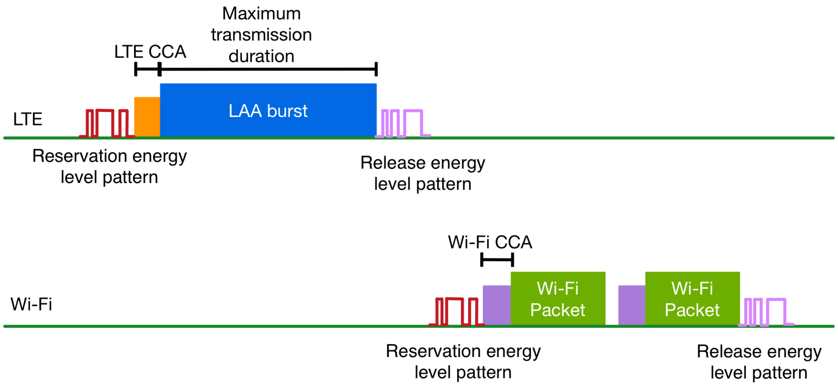

Figure 4.9: Inter-Radio Access Technology (RAT) TDMA.

Before an LTE or a Wi-Fi transmission, the eNB or the AP tries to gain access to the medium by broadcasting a reservation energy level pattern. When a network detects and interprets such a signal, it postpones its transmissions. The network that transmitted the reservation pattern can gain access to the medium for a period of time smaller or equal to a maximum transmission duration. The choice of the maximum transmission duration that a network can access the medium is very important, as it should guarantee that the medium is not monopolized and every network can access it in a fair way. When the network completes a transmission or when the maximum transmission duration is reached, then it broadcasts a release energy level pattern. At this point, another or the same network can reserve the medium in order to transmit.

During the transmission duration, an eNB schedules resource blocks the UEs that are attached to it, while in case of Wi-Fi, the nodes compete for the medium using the traditional CSMA/CA technique. Before the start of transmission in the reserved timeslot, the network that requests access to it, must sense the medium for ongoing transmissions by networks that are not part of the cooperation mechanism in order to prevent interference with them.

From the above description, it is clear that the implementation of an inter-RAT TDMA mechanism requires small modifications for both LTE and Wi-Fi protocols. These modifications will render both technologies capable of transmitting, detecting and interpreting the in-band energy level patterns, so that they can reserve the medium or postpone their transmissions.

4.5 Indirect Cooperation via a Third-Party Entity

4.5.1 Introduction

The previous section described different cooperation techniques, wherein the participating LTE and Wi-Fi networks can cooperate directly by sending, sensing and interpreting in-band energy patterns. This section goes one step further and discusses the cooperation possibilities, when LTE in the unlicensed spectrum and Wi-Fi are able to exchange messages and express their requirements through a third-party entity. This third-party entity can communicate with both technologies in order to exchange the necessary information that can lead to optimal spectrum usage and enhance the user experience. The third-party entity can be either a central entity, such as a Central Coordination Entity (CCE), or it can be deployed in a distributed manner (Distributed Coordination Entity (DCE)). In the DCE case, a third-party entity must be connected with the base station of each network (LTE eNB or Wi-Fi AP). Thus, the different entities must communicate with each other in order to convey the messages from one network to the other. In this case, the complexity of the cooperation schemes increases. For this reason, in the rest of the article we focus on the usage of the CCE as a third-party entity. However, for the proposed techniques, both a CCE or a DCE can be used.

It is expected that this kind of cooperation can lead to better spectral management results compared to the previously-mentioned techniques in Section 4.4, as both technologies can explicitly declare their requirements and speak indirectly to each other through the CCE. Such a type of cooperation between LTE and Wi-Fi can offer high flexibility, which can lead to the implementation of advance cooperation techniques. Moreover, cooperation of this type does not increase the complexity of the operation of the LTE and Wi-Fi transmitter and receiver. However, the implementation of the CCE, as well as the requirement for the CCE entity as part of the network adds extra complexity to the design of such a system.

The Wi-Fi APs and the LTE eNBs can be connected to the CCE by either a wired or a wireless link. In the case of a wired connection, the on-demand communication among the networks and the CCE is guaranteed. Of course, wired connectivity limits the flexibility in terms of deployment. These deployment scenarios are limited mainly to indoor deployments, such as in office environments. On the contrary, wireless communication offers higher deployment freedom, but the transmission of the messages between the CCE and the wireless technologies has to deal with the same well-known issues that arise in every wireless communication, such as interference. For simplicity, in the rest of the paper, we assume that there is wired communication among the CCE, the eNBs and the APs.

Furthermore, the CCE must ensure synchronization between the networks that participate in the cooperation scheme. The synchronization among the networks for such cooperation techniques is often critical, as the exchange of information and the access to the medium need to be done in precise time instances. The synchronization requirements depend on each single technique, and therefore, we discuss them in the following subsections.

The rest of this section analytically describes different possible cooperation methodologies that can be applied, when a CCE is available among LTE and Wi-Fi. In addition, for each method, we discuss the changes that are required for both LTE and Wi-Fi protocols.

4.5.2 Adjustment of LTE Transmission Based on Wi-Fi Requirements

As discussed in Section 4.3.4.1, LTE LAA, in its current form and after a successful CCA, starts transmitting for a duration of 2–10 ms, depending on the channel access priority class to which it belongs (Table 4.2). Thus, the duration of an LTE transmission is much longer than a typical transmission duration of Wi-Fi (typically a few hundreds of μs), which transmits only one packet after a successful CCA.

In order to balance LTE occupation of the wireless medium versus Wi-Fi, an event-based coordination technique can be applied, which adjusts the LTE transmission duration based on the requirements of Wi-Fi. Additionally, a mute period at the end of an LTE transmission is introduced, as is depicted in Figure 4.8. Wi-Fi can exploit this period to gain additional access opportunities to the medium resulting in a longer time period of Wi-Fi transmissions.

The proposed scheme requires that both LTE and Wi-Fi perform a CCA before a transmission. This guarantees that the regional regulations are satisfied and that the cooperation scheme is able to coexist with other potential co-located legacy networks. Figure 4.10 illustrates the proposed network architecture.

Initially, when a new Wi-Fi network is activated, the AP collects the requirements of the Stations (STAs) that are connected to it and sends them to the CCE. The AP keeps collecting the STAs requirements periodically. Typically, the requirements of a network change on a relatively slow timescale. Thus, this period can be in terms of tens of milliseconds up to a few seconds. When the AP collects new requirements, it checks the variation compared to the previous state reported to the CCE. If this variation exceeds a defined threshold, then the AP reports the new requirements to the CCE. The Wi-Fi AP's report to the CCE may consist of two different types of information. The first one comprises the summarized statistics of the load of each STA. The second type refers to the future requirements for the next time frame, reported by the STA during the current time frame. These future requirements correspond to a summarized bit rate per second for every Wi-Fi Multimedia (WMM) Access Categories (ACs). For the 802.11 standard, four different WMM priority classes are defined for handling the data traffic regarding

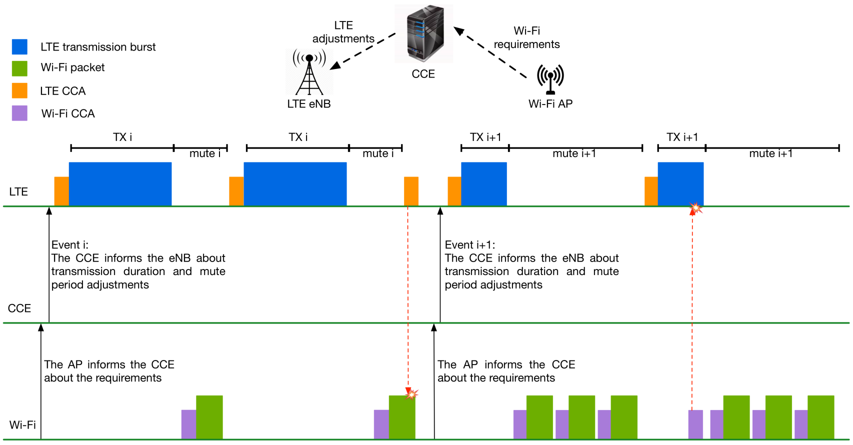

Figure 4.10: Adjustment of LTE transmission based on Wi-Fi requirements.

the QoS requirements. These classes are the following:

- AC_BK (background traffic)
- AC_BE (best effort traffic)
- AC_VI (video traffic)
- AC_VO (voice traffic)

After the CCE receives the new requirements, it evaluates them, and if a change of LTE transmission behavior is needed, it triggers an event and informs LTE about the new transmission duration and the new length of the mute period. Hence, the next LTE transmission will be done according to the new configuration. In the case of multiple LTE networks, the transmission duration and mute period should be synchronized among them. This way, a scenario according to which an LTE transmission occurs during the mute period of another LTE network occupying the Wi-Fi grant can be avoided.

This way, under a heavily loaded Wi-Fi network or if Wi-Fi needs to transmit delay-sensitive traffic, the coordinator schedules a shorter transmission duration for LTE and/or a longer mute period after a transmission. The ratio of LTE transmission duration and LTE mute duration must be chosen carefully, so that LTE does not suffer from continuous short transmission durations and long mute timeslots in the unlicensed spectrum. Hence, CCE must keep a record of the last configurations of the LTE transmission and mute duration over time. This way, it will be able to maintain a balance between serving the Wi-Fi requirements and giving equal channel access opportunities to all of the cooperating networks.

For the cooperation technique that is described in this section, no synchronization is needed between Wi-Fi and LTE, since there is no need for synchronized access to the medium between the different technologies.

The implementation of such a cooperation scheme requires some changes to both LTE and Wi-Fi. Regarding LTE, it needs to be extended in a way that it can receive and use the transmitted messages by the CCE. This extension also includes the introduction of the additional mute period after a transmission in the unlicensed spectrum and variable transmission period. On the other hand, the Wi-Fi STA part has to be extended to be capable of reporting the transmission requirements to the AP. Additionally, the AP must be able to collect, evaluate and report these requirements to the CCE. Finally, a sophisticated CCE needs to be employed. This CCE must be able to collect the requirements from the Wi-Fi AP, process them and inform the eNB about the new configuration parameters. The described cooperation scheme targets serving the Wi-Fi requirements by adjusting the transmission duration of LTE, concurrently maintaining equal channel access opportunities among the participating networks. This technique can be implemented with a relatively small effort, as it requires small modifications for LTE and Wi-Fi as described above. On the other hand, it does not take into account the requirements of LTE. In the next section, a more complex, but enhanced technique is proposed, in which the CCE schedules LTE and Wi-Fi transmissions, considering the requirements of both networks.

4.5.3 Adjustment of LTE and Wi-Fi Transmission Based on Requirements and History

In a more sophisticated approach than the technique described in the previous section, the CCE adjusts both LTE and Wi-Fi transmission timeslots based on their requirements, as well as the channel activity history.

In order to control the duration and the frequency of LTE bursts, we assume variable transmission duration, followed by a variable mute period, in an event-based way similarly to the previous technique. Furthermore, both LTE and Wi-Fi networks must perform a CCA before a transmission in order to be compliant with the regional regulations and respect potential transmissions from other networks that do not participate in the cooperation scheme.

In a similar way to the previous section, when a new Wi-Fi or LTE network is activated, the AP or the eNB collects and sends the network requirements to the CCE. Then, the AP or the eNB keeps collecting requirements periodically. This period can be in terms of tens of milliseconds up to a few seconds and can vary between different networks. The new requirements are compared to the previous state reported to the CCE. If the variation exceeds a defined threshold, then they are sent to the CCE. The Wi-Fi requirements are the ones that have been described in Section 4.5.2. Similarly, the LTE eNB informs the CCE about the transmission load of the LTE network.

When the coordinator receives the requirements, then it decides about the LTE transmission duration and mute period based on the current requirements (e.g., summarized bit rate per second) and the history of transmissions. The history of transmissions represents a moving time window that tracks the average channel utilization for each participating network. The decision can be made, taking into account different weights of the history and the current requirements. To this end, the values of p and $1-p$, where $0 \leq p \leq 1$, are used to express the weights of the current requirements and history that will be used respectively. Initially, history records are not available. Hence, only the current requirements are taken into consideration.

The weights of the current requirements and history will be used by the scheduler of CCE to compute the new duration of the LTE transmission and the new duration of the LTE mute period. Hence, when a network must transmit mainly delay-sensitive traffic, then the weight of the current requirements will be higher than the weight of history, as in this case, the traffic must be delivered on time. In a similar way, when best-effort traffic has to be transmitted, then the history of the channel utilization may have a higher weight in the final decision. If a change to the transmission behavior of LTE is needed, then the CCE triggers an event and informs LTE about the new configuration of transmission. The next LTE transmission will be done according to the new configuration. Again, in case of multiple eNBs, the transmission duration and mute period should be synchronized. Figure 4.11 presents the aforementioned cooperation technique.

The flowchart of the proposed cooperation method is shown in Figure 4.12. When needed, the eNB and the AP inform the coordinator about their new requirements. When the coordinator receives the requirements, it evaluates them and decides if modifications to the LTE transmission duration and mute period are required, as described above. Then, the coordinator informs the participating networks about its decision and updates its database. Based on the coordinator's decision, the LTE adjusts its transmission duration and the mute duration for the next time frame giving the necessary slots to Wi-Fi.

In this technique, synchronization between Wi-Fi and LTE is not critical, as there is no need for synchronized access to the medium between the wireless technologies that participate in the cooperation scheme.

Similar to the method described in Section 4.5.2, such a cooperation mechanism requires changes for both LTE and Wi-Fi, so they can inform the CCE about their requirements. Additionally, extensions are required to eNB and AP, so they can receive and use the information transmitted by the CCE. Finally, the CCE itself has extra complexity compared to the previous method, as it needs to keep track of the transmission for all of the participating networks and it has to decide about

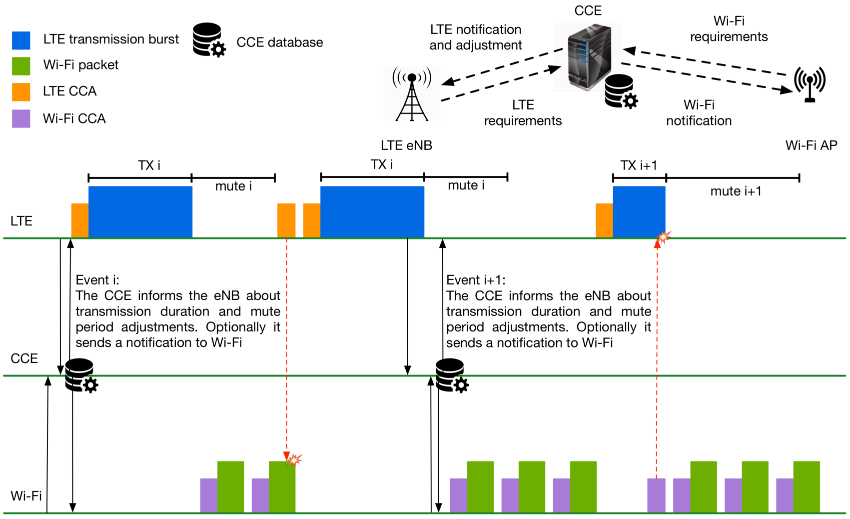

Figure 4.11: Adjustment of LTE and Wi-Fi transmission based on requirements and history.

the sharing of the channel based on complex criteria.

4.5.4 Negotiation between LTE and Wi-Fi

The method described in the previous section gives to the coordinator the possibility to decide, in the beginning of a time frame, the duration of the LTE transmissions and the following mute period. These durations remain stable during the whole time frame duration. In a different approach, the CCE can schedule variable durations of LTE transmission and mute periods in the same time frame. This technique can offer higher transmission flexibility and can better serve the QoS requirements as the networks can access the medium in a more dynamic way. The proposed methodology is illustrated in Figure 4.13.

As can be seen, the time domain is divided into time frames with a range from tens of milliseconds up to a few seconds. In the beginning of each frame, there is a negotiation phase during which the participant networks of the cooperation scheme report their requirements to the coordinator. As presented in Section 4.5.3, the coordinator keeps a record of the channel activity. Hence, it knows the percentage that each network has occupied the channel in the past. When the coordinator receives the requirements during the negotiation phase, it divides the time frame into slots and assigns them to the different networks based on their demands and the history of the channel activity. The proportion of the current requirements and history will be decided in an advanced way, similar to the one described in

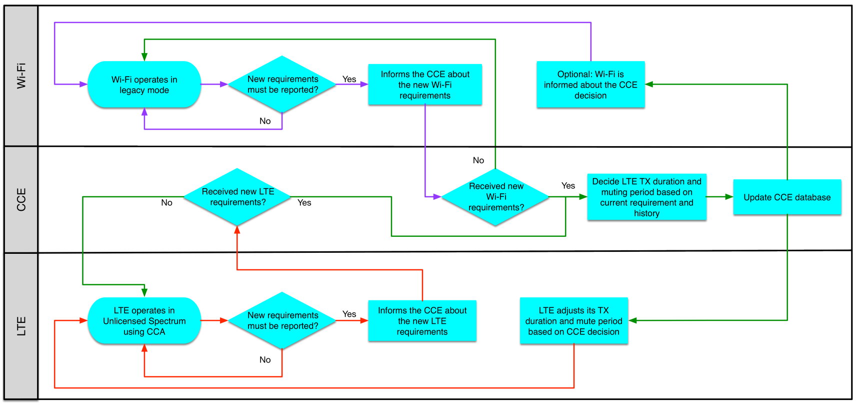

Figure 4.12: Flowchart of LTE and Wi-Fi transmissions adjustment by Central Coordination Entity (CCE).

Section 4.5.3. In this technique, the wireless technologies access the medium in an inter-technology TDMA way. When a timeslot is assigned to an LTE network, the eNB schedules resources for the UEs that are attached to it. On the other side, if a timeslot is assigned to a Wi-Fi network, then the Wi-Fi nodes are competing for the medium using the traditional CSMA/CA method. Before a transmission, both LTE and Wi-Fi networks must perform a channel estimation to ensure that the channel is free from potential ongoing transmissions by other networks that do not participate in the cooperation mechanism. If the channel is sensed as busy, then the network continues to sense the wireless medium till the end of the assigned slot. If the medium becomes idle, the corresponding network starts a transmission for the remaining time. The CCE can take into account such potential cases for future scheduling decisions in order to assign longer or more slots to the network that missed one or more assignments during the previous frame(s).

In this technique, the coordinator needs to ensure synchronization of the participating networks in a frame time domain. This way, the networks will be able to express their requirements and negotiate about the spectral requirements during the negotiation phase. Additionally, the participating networks will be able to access the corresponding assigned LTE and Wi-Fi time slots that the scheduler creates in a synchronized manner.

Such a cooperation mechanism requires modifications of LTE and Wi-Fi, so they can express their requirements during the negotiation phase. Moreover, the networks should be able to interpret the messages sent by the CCE and transmit only during the timeslots that have been assigned to them by the coordinator. Additionally, a sophisticated CCE needs to be implemented, which will be able to receive the requirements from different networks and to assign timeslots using ad-

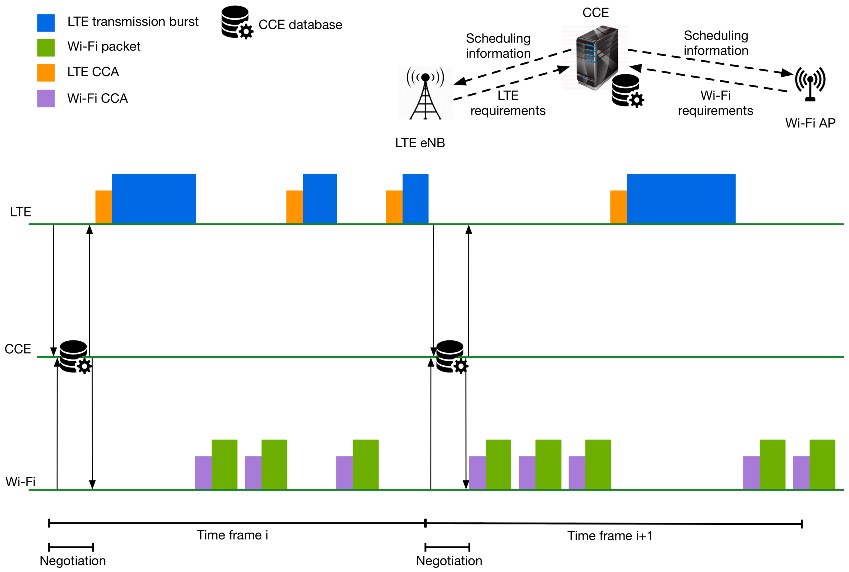

Figure 4.13: Negotiation phase between LTE and Wi-Fi and timeslot assignment.

vanced methods, taking into account the current requirements and the history of the channels' occupancy.

4.6 Comparison of the Proposed Schemes

This section highlights the main differences between the proposed techniques that have been discussed in the previous sections. Table 4.3 summarizes these differences in terms of the modifications that each technique requires, the synchronization requirements, the complexity and the performance of each cooperation scheme.

The complexity of each technique is divided into two different aspects named expected implementation complexity and information exchange overhead. The expected implementation complexity indicates the number of modifications to the current standards and protocols of each wireless technology that each proposed technique requires. For instance, the "Enhanced LTE LAA" technique requires only a few changes to the LTE LAA standards in order to allow variable mute and transmission opportunity periods, as well as transmission, reception and interpretation of the special energy patterns. On the other hand, the "adjustment of LTE and Wi-Fi transmission based on requirements and history" technique requires an average implementation effort, as it involves a sophisticated coordinator unit that must be capable to communicate with the co-located networks and tune the LTE parameters based on different parameters (current requirements and history).

The information exchange overhead expresses the amount of information or signals that are exchanged between the co-located wireless networks towards the attainment of cooperation according to each technique. For example, the "Inter-RAT TDMA" cooperation scheme requires the exchange of several energy level patterns between the co-located networks, so that they can reserve and release the medium prior to and after a transmission. In contrast, according to the "adjustment of LTE transmission based on Wi-Fi requirements" technique, a Wi-Fi network informs the coordinator about its requirements in an event-based manner and in a relatively slow timescale (tens of milliseconds up to a few seconds). Thus, such technique is expected to have a low information exchange overhead.

Furthermore, the performance of each proposed cooperation scheme is divided into two aspects named degree of cooperation and expected spectral efficiency. The degree of cooperation indicates the eagerness of each technique to cooperate. The lower the degree of cooperation, the lower the performance of the cooperation technique. For instance, the "negotiation between LTE and Wi-Fi" technique offers a high degree of cooperation, as the participating networks exchange information and negotiate about the spectral requirements towards the best possible serving of their QoS requirements. In contrast, the "inter-RAT TDMA" technique offers a low degree of cooperation as a network simply reserves the medium for the shortest possible period in an altruistic manner.

The expected spectral efficiency indicates the expected capability of each proposed technique to manage and share the spectrum between the different co-located wireless technologies in an efficient way. For instance, the "negotiation between LTE and Wi-Fi" technique is expected to have a high spectral efficiency, as it selects variable LTE and Wi-Fi slots based on the negotiation result between the co-located technologies.

Similar to the standalone operation of wireless technology, where there is no other competitor for the wireless resources, the number of the nodes operating in each technology will have an impact on the spectral efficiency that each technique can provide. Regarding the LTE network, if there are many UEs, then the resources will be divided in to the different UEs by the LTE scheduler. When there are multiple Wi-Fi nodes, then more nodes would compete during the LTE idle slots decreasing the provided spectral efficiency. In this case, a TDMA channel access scheme for Wi-Fi could improve the achieved spectral efficiency. Additionally, an increased number of nodes corresponds to a higher amount of information or signals that have to be exchanged between the networks (or between the networks and the third-party entity) according to each cooperation technique. Hence, the higher the number of the nodes operating in each technology, the higher the information exchange overhead and the complexity of the cooperation schemes.

Table 4.3: Comparison of the different proposed cooperation schemes

Cooperation type	Cooperation technique	Modifications required	Sync required	Complexity		Performance	
				Expected implementation complexity	Information exchange overhead	Degree of cooperation	Expected spectral efficiency
Direct cooperation via in-band energy level patterns	Enhanced CSAT	Transmission, detection and recognition of special energy level patterns for LTE and Wi-Fi Variable mute and transmission period for LTE MAC layer modifications for LTE and Wi-Fi	Between the different networks	Low	Medium	Low	Low
	Enhanced LTE LAA	Transmission, detection and recognition of special energy level patterns for LTE and Wi-Fi Variable mute and transmission period for LTE MAC layer modifications for LTE and Wi-Fi	No	Low	Medium	Low	Low
	Advanced frequency selection	Modifications similar to the previous two methods Frequency selection procedures for LTE	No	Medium	Medium	Low	Medium
	Inter-RAT TDMA	Transmission, detection and recognition of special energy level patterns for LTE and Wi-Fi Variable mute and transmission period for LTE MAC layer modifications for LTE and Wi-Fi	No	Low	High	Low	High
Indirect cooperation via a third-party entity	Adjustment of LTE transmission based on Wi-Fi requirements	CCE procedures Communication between CCE, LTE eNB and Wi-Fi AP Variable mute and transmission period for LTE MAC layer modifications for LTE and Wi-Fi	Between multiple eNBs	Medium	Low	Medium	Medium
	Adjustment of LTE and Wi-Fi transmission based on requirements and history	CCE procedures Communication between CCE, LTE eNB and Wi-Fi AP Variable mute and transmission period for LTE MAC layer modifications for LTE and Wi-Fi	Between multiple eNBs	Medium	Low	High	High
	Negotiation between LTE and Wi-Fi	CCE procedures Communication between CCE, LTE eNB and Wi-Fi AP Variable mute and transmission period for LTE MAC layer modifications for LTE and Wi-Fi	Between the different networks	Medium	Low	High	High

4.7 Conclusions and Future Work

Towards 5G, the number of HetNets is expected to increase rapidly. These HetNets consist of different well-established wireless technologies that operate next to each other. Each of these technologies has its own user target group, as it is suitable for specific applications (sensor networks, D2D communications, M2M communications, etc.). Among them, Wi-Fi is the most popular and widely-used wireless technology in the unlicensed spectrum. Recently, LTE in the unlicensed spectrum has been introduced, as it is a technology that can play an important role in dealing with the tremendous wireless traffic increment. Hence, scenarios in which co-located LTE and Wi-Fi networks operate in the same band will soon become very common. Based on this fact, the research community needs to look into cooperation techniques among different technologies in order to use the wireless spectrum as efficiently as possible.

In this article, we describe different cooperation techniques that can be applied between co-located LTE and Wi-Fi networks. These techniques are classified into two main categories. According to the first one, the networks cooperate directly by sending, receiving and interpreting in-band special patterns. In the second category, the cooperating networks can intercommunicate indirectly using a third-party entity such as a CCE. Each technique requires different implementation effort and offers different cooperation flexibility and spectral efficiency. Subsequently, for each proposed technique we analyze the open issues and challenges, as well as the required changes to the LTE and Wi-Fi protocols taking into account regional regulations.

The concepts that are described in this article will be used as a cornerstone for our future work. In the near future, this work can be extended towards the implementation and the comparison of the proposed techniques by initially performing simulations according to the performance indicators as they are mentioned in Table 4.3. Further, implementation and evaluation based on real hardware can also be done using the LTE and Wi-Fi infrastructure of the W-iLab2 testbed at imec. This way, each cooperation technique can be examined in detail and the analytical results of the provided fairness and spectral efficiency can be obtained. This work can further contribute to the ongoing research and standardization towards an efficient and fair spectral sharing between LTE and Wi-Fi.

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5

An Adaptive LTE Listen-Before-Talk Scheme Towards a Fair Coexistence with Wi-Fi in Unlicensed Spectrum

In the previous chapter, several cooperation schemes have been proposed targeting fair spectrum sharing between LTE and Wi-Fi. In this chapter, an adaptive LTE LBT scheme that can provide fair coexistence with Wi-Fi is studied. This scheme uses variable TXOP for LTE, which is followed by a variable muting period that gives channel access opportunities to other co-located networks. The chapter discusses the problem of enabling fairness in the unlicensed spectrum, where many and diverse networks operate next to each other. The proposed scheme is implemented using an event-based simulation platform and it is evaluated for different scenarios of high interest. This chapter is a modified version of the original homonymous article, which is published in the Telecommunication Systems Journal.

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Abstract The technological growth combined with the exponential increase of wireless traffic are pushing the wireless community to investigate solutions to maximally exploit the available spectrum. Among the proposed solutions, the operation of Long Term Evolution (LTE) in the unlicensed spectrum (LTE-U) has attracted significant attention. Recently, the 3rd Generation Partnership Project (3GPP) announced specifications that allow LTE to transmit in the unlicensed spectrum using a Listen Before Talk (LBT) procedure, respecting this way the regulator requirements worldwide. However, the proposed standards may cause coexistence issues between LTE and legacy Wi-Fi networks. In this article, it is discussed that a fair coexistence mechanism is needed to guarantee equal channel access opportunities for the co-located networks in a technology-agnostic way, taking into account potential traffic requirements. In order to enable harmonious coexistence and fair spectrum sharing among LTE-U and Wi-Fi, an adaptive LTE-U LBT scheme is presented. This scheme uses a variable LTE transmission opportunity (TXOP) followed by a variable muting period. This way, co-located Wi-Fi networks can exploit the muting period to gain access to the wireless medium. The scheme is studied and evaluated in different compelling scenarios using a simulation platform. The results show that by configuring the LTE-U with the appropriate TXOP and muting period values, the proposed scheme can significantly improve the coexistence among LTE-U and Wi-Fi in a fair manner. Finally, a preliminary algorithm is proposed on how the optimal configuration parameters can be selected towards harmonious and fair coexistence.

5.1 Introduction

Over the last years, the technological growth has led to a tremendous increase of wireless devices such as smartphones, tablets, laptops and wearable technologies. Additionally, the number of electronic devices that exchange information wirelessly is growing day by day, pushed by the evolution and consolidation of the Internet of Things (IoT). According to Qualcomm, the amount of wireless traffic is expected to further increase by a factor of 1000 by 2020 [1]. This massive amount of information is exchanged between devices using different types of technologies such as Long Term Evolution (LTE), IEEE 802.11, IEEE 802.15.4 and Bluetooth. Lately, sub-gigahertz bands are exploited by technologies like LORA and SIGFOX in order to achieve wide range communications. Additionally, high frequency bands such as mmWave are used for multi-gigabit speeds (IEEE 802.11ad). It becomes clear that the wireless network capacity will soon become a bottleneck for the increased wireless traffic.

Concurrently, the licensed spectrum used by the mobile operators becomes very scarce. The limitation of the licensed spectrum in combination with the high cost of a licensed frequency band have pushed the mobile operators to investigate other technological solutions that can support in meeting the ‘1000x challenge’ requirements. These solutions include among others, enhanced massive Multiple-Input Multiple-Output (MIMO), Carrier Aggregation, cloud computing services, as well as LTE operation in the unlicensed spectrum (LTE-U). Among various other solutions, the last one has attracted significant attention from the wireless community. Several mechanisms, such as Listen Before Talk (LBT) have been proposed towards the coexistence of LTE-U and other well-established technologies in the unlicensed spectrum, such as Wi-Fi [2].

In markets like the U.S., China and South Korea where a Clear Channel Assessment (CCA) mechanism (also known as LBT) is not required, LTE can operate in the unlicensed spectrum using techniques such as Carrier Sense Adaptive Transmission (CSAT) [3].

Recently, key players of the mobile world have proposed standards to the 3rd Generation Partnership Project (3GPP), which specify the LTE operation in unlicensed spectrum. 3GPP announced the operation of LTE Licensed-Assisted Access (LTE LAA) [4], as an enhancement towards 3GPP LTE Release 13. LTE LAA requires a CCA procedure before each transmission in the unlicensed spectrum. This way, the mechanism can be applicable worldwide, including markets like Europe and Japan, where CCA is mandatory.

In order to decouple LTE from the operators, leading wireless stakeholders proposed the LTE operation solely in the unlicensed spectrum as a standalone wireless solution. To this end, they formed the MulteFire Alliance [5]. Hence, LTE can be deployed by Internet Service Providers (ISPs), building owners, cable companies, etc. The underlying technique proposed by the alliance builds on elements of 3GPP LTE LAA.

Although the LTE LAA standard defines that a CCA procedure must be performed before a transmission burst, it also defines four different channel access priority classes. Each channel access priority class specifies among others the duration of the transmission burst that follows a successful CCA procedure. This duration ranges from 2 ms to 10 ms [2]. On the contrary, a Wi-Fi packet transmission when frame aggregation is not enabled or supported by the 802.11 standard typically lasts a few hundreds of μs [6]. Furthermore in [7], it has been assessed that for 802.11n with frame aggregation, 50% of the packets are transmitted within 30 μs, while 80% of the packets are transmitted within 1 ms. It is clear that the ratio between LTE and Wi-Fi channel occupancy is not balanced. This can result to unfair coexistence between co-located LTE LAA and Wi-Fi networks.

In this article, we discuss a way that fairness can be achieved between LTE-U and Wi-Fi. We define a new adaptive LTE-U transmission scheme according to which LTE can transmit in unlicensed spectrum using a variable transmission opportunity (TXOP) time. This TXOP period is followed by a variable muting period in order to give channel access opportunities to other potentially co-located networks, such as Wi-Fi. Before a TXOP, LTE must perform a CCA procedure in order to determine the availability of the channel. This scheme can be used for LTE transmissions in the unlicensed spectrum next to the primary cell that an operator uses in the licensed spectrum similar to LTE LAA. The proposed scheme is evaluated through simulations. Finally, we discuss how the configurations of TXOP and muting period can be selected by a network in order to provide fair coexistence. The main contribution of this work is summarized as follows:

- Discussion about fairness and definition of fairness as equal sharing of the wireless resources in a technology-agnostic manner
- Verification of the problem by evaluating the coexistence between LTE LAA and Wi-Fi, when Wi-Fi operates in a traditional way, meaning that it does not support or it does not use frame aggregation
- Proposal of a new adaptive LTE-U transmission scheme that uses a variable TXOP followed by a variable muting period. The proposed scheme performs a channel estimation before a transmission to ensure the availability of the channel
- Discussion about the selection of the TXOP and muting period combinations that can offer fair coexistence between LTE-U and Wi-Fi

The remainder of the article is organized as follows. Section 5.3 discusses the current literature on LTE-U and especially LTE LAA. Section 5.4 defines the problem that arises when LTE LAA coexists with traditional Wi-Fi networks that do not use frame aggregation and describes the proposed solution. Next, in Section 5.5 we discuss about fair coexistence in unlicensed spectrum and the approach that we follow in this article. Section 5.6 presents the simulation platform that has been used. In Section 5.7, we discuss the simulation scenarios that are studied. Then, in Section 5.8, we present and discuss the obtained results for each investigated scenario. In Section 5.9, we discuss the way that a selection of the configuration parameters can be done for the proposed scheme towards fair coexistence. Finally, in Section 5.10, we conclude the paper and discuss plans for future work.

5.2 LTE and Wi-Fi

In Sections 2.3 and 2.4 of Chapter 2, we present an overview of the main characteristics of Wi-Fi [6] and LTE [8] that lead to coexistence issues when the two technologies operate next to each other in their traditional form.

5.3 Related work

In our previous work [9], we studied the impact of traditional LTE operating in unlicensed spectrum on Wi-Fi using Off-The-Shelf (OTS) hardware equipment using the LTE testbed of IMEC [10]. In this study, three different levels of LTE signal have been examined, representing different possible levels of LTE impact on Wi-Fi. The results show that the Wi-Fi performance, in terms of throughput and latency, can be significantly affected by LTE. In [11], the authors performed an experimental evaluation to study the impact of LTE LAA on Wi-Fi performance in indoor office environment. The study includes analysis of LTE LAA interference for five different scenarios. Based on this analysis the authors provide LTE LAA Medium Access Control (MAC) designs to deal with coexistence issues with Wi-Fi. Several other studies [12] [13] [14] evaluate the Wi-Fi performance degradation based on mathematical models and simulations. All studies come to the same conclusion, namely that coexistence mechanisms are required to enable coexistence between co-located LTE and Wi-Fi networks.

The authors in [15] evaluate through simulations the performance impact of LTE and Wi-Fi when both networks operate in the same frequency. They propose a coexistence mechanism similar to CSAT that exploits periodically blank LTE subframes during an LTE frame in order to give opportunity to Wi-Fi to transmit. They conclude that the network topology, as well as the number and order of the blank subframes lead to different coexistence results.

Towards a global coexistence technique that respects the regional regulations, 3GPP announced the LTE LAA standards in Release 13, including the description of a CCA procedure [2]. Initially, LTE LAA is scheduled to operate for DL only and within the 5 GHz channel. Towards Release 14, it is expected to be extended to 2.4 GHz unlicensed band and for both DL and UL traffic. The transmission in the unlicensed spectrum can be done via a secondary cell operating alongside the primary cell owned by the operator. This feature can be enabled using the Carrier Aggregation mechanism that has been introduced in 3GPP LTE Release 10 [16].

In [17], the authors provide a description of the LTE LAA mechanisms including motivation and use cases to which it can be applied. They present a coexistence evaluation methodology and results, which have been contributed by 3GPP.

The authors of [18] present a detailed overview of LTE LAA in Release 13. They show how the introduction of CCA and the discontinuous transmission impose changes in different LTE components such as the DL physical channels, the hybrid automatic repeat request (HARQ) feedback procedures, etc. Simulation results are presented to show that coexistence with Wi-Fi can be enabled in a range of scenarios. Moreover, an overview of LTE LAA enhancements beyond Release 13 is given.

In [19] two non-coordinated and two coordinated network management approaches to enable coexistence are proposed. Regarding the non-coordinated techniques, the first one proposes eNB to perform CCA on different channels and to switch to a different channel after a transmission, while the second proposes LTE to offer transmission opportunities of variable duration to Wi-Fi after a transmission based on the occupancy of the medium. Concerning the coordinated methodologies, the first one proposes a Network Function Virtualization (NFV) interconnection to combine the Wi-Fi network and the LTE-U service provider. Channel selection and seamless transfer of resources between the two technologies can be enabled, using the in-the-cloud control of distributed Access Points (APs). The second method proposes the management of coexistence using the X2 interface among the eNBs. The eNBs can exchange information and schedule Almost Blank Subframes (ABS) in different subframes giving this way more opportunities to any Wi-Fi network that is located potentially within their proximity. In the aforementioned schemes, the different Radio Access Technologies (RATs) are under the control of the same mobile operator.

The authors in [20] propose an LBT protocol for LTE LAA that enhances the coexistence with Wi-Fi and increases the overall system performance. This LBT scheme consists of two different mechanisms named on-off adaptation for channel occupancy time and short-long adaptation for idle time. The first mechanism is responsible to adapt the channel occupancy time of LTE based on the load of the network, while the second one adapts the idle period based on the Contention Window (CW) duration of Wi-Fi.

In [21], the authors propose an LBT mechanism for LTE LAA that aims to share the medium in a fair way towards the increase of the overall system performance. The mathematical analysis of the proposed LBT scheme is validated via simulations. The results show that a proper selection of LAA channel occupancy and backoff counter can increase the performance of Wi-Fi.

In [22], the coexistence between LTE LAA and Wi-Fi is studied using LBT category 4 channel access scheme. The behaviour of LAA eNB is modelled as a Markov Chain and the obtained throughput is adopted as performance metric. The proposed LBT scheme uses an adaptive CW size for LTE LAA. According to the results, the proposed scheme outperforms the fixed CW size.

The authors in [23] describe and evaluate a channel switch function that is used to determine the LTE LAA channel dynamically. This way, LTE LAA can exploit the spectrum in a more flexible way. They propose an enhanced LBT scheme with channel switch that uses a frozen period to select the appropriate channel. The channel switch is done based on a proportional fair based dynamic channel switch method that is analytically presented. The results show that the proposed scheme can increase the overall system performance.

In [24], a MAC layer for LTE-U is proposed that uses an LBT algorithm and channel reservation packets. Both synchronous and asynchronous LBT are examined. Additionally, improvements to the LTE link adaptation algorithm are proposed in order to cope with potential collisions. Simulation results indicate that the performance of Wi-Fi can be improved by the proposed MAC design. Furthermore, the channel reservation mechanisms increase the LTE-U cell edge performance.

In our previous work [25], we extensively studied the concept of LTE-U. Initially, we provide a detailed analysis of the current state-of-the-art regarding LTE-U and Wi-Fi. Furthermore, the article presents a classification of techniques that can be applied between co-located LTE and Wi-Fi networks. This classification in combination with the study of the literature revealed the lack of cooperation schemes among co-located networks that can lead to more optimal use of the available spectrum. In order to fill this gap, several concepts of cooperation techniques that can enhance the spectral efficiency between coexisting LTE and Wi-Fi networks are proposed. Additionally, the proposed cooperation schemes are compared between each other in terms of complexity and performance.

Finally, the authors in [26] provide a detailed survey of the coexistence of LTE-U and Wi-Fi on 5 GHz with the corresponding deployment scenarios. They provide a detailed description of the coexistence-related features of LTE-U and Wi-Fi, the coexistence challenges, the differences in performance between the two different technologies and co-channel interference. They extensively discuss the proposed coexistence mechanisms between LTE-U and Wi-Fi in the current literature. Furthermore, the survey discusses the concept of the scenario-oriented coexistence, in which coexistence-related problems are solved according to different deployment scenarios.

Although the 3GPP standards specify that the channel must be sensed by a CCA procedure before a transmission, the ratio between LTE LAA and Wi-Fi transmission opportunities is not balanced, especially in the case that Wi-Fi does not support or use frame aggregation. According to the best of our knowledge, the current literature lacks of a mechanism that can adapt the LTE-U channel access after a CCA in order to provide equal channel opportunities to other co-located networks such as Wi-Fi. The following aspects render our proposal novel and valuable. Firstly, the proposed scheme is flexible as it adapts the LTE-U channel access in order to provide fair coexistence with networks in unlicensed spectrum based on various parameters such as the number of the co-located networks and the type of traffic that has to be served (e.g. delay-sensitive traffic). Secondly, the CCA procedure ensures that the mechanism can be applicable worldwide. Thirdly, this scheme can provide fair coexistence not only to Wi-Fi but also to other well-established technologies in unlicensed spectrum, such as 802.15.4 and Bluetooth. Finally, the proposed variable TXOP followed by a variable muting period does not have an impact on time-sensitive LTE traffic, as it can still be transmitted via the licensed band of the operator.

5.4 Problem definition and proposal description

Recently, 3GPP announced the LTE LAA standards as part of LTE Release 13. LTE LAA defines that a CCA procedure [2] must be performed before an LTE transmission in the unlicensed spectrum. This way, the standard can be applicable worldwide, as it respects the regional regulations in markets like Europe and Japan where a CCA procedure is mandatory.

Initially, LTE LAA (as defined in Release 13) is scheduled to operate within the 5 GHz unlicensed spectrum and for Downlink (DL) traffic only, while the Uplink (UL) traffic will be maintained in the licensed spectrum. In a later phase towards Release 14, it is expected to be extended to 2.4 GHz unlicensed band including both DL and UL traffic. According to LTE LAA Release 13, an eNB will be able to activate and deactivate a secondary cell operating in the unlicensed spectrum. Via this cell only DL data traffic can be sent through the Physical DL Shared Channel (PDSCH). The LTE control signals and the UL traffic will be maintained in the licensed anchor via the Physical UL Shared Channel (PUSCH). Especially for the LTE control signals whose transmission is time-critical, the licensed anchor can guarantee a safe and interference-free transmission.

Before a transmission, an eNB must perform the CCA procedure in order to sense the channel in the unlicensed spectrum. When the channel is sensed as busy, the eNB must defer its transmission and perform an exponential backoff. If the medium is sensed as idle, the eNB starts a transmission burst with a duration varying form 2 ms up to 10 ms, depending on selected channel access priority class. Table 5.1 shows the definitions of the different channel access priority classes. The smaller the number of the class, the higher the priority. In this table, m_p is the number of slots in a defer period, while CW_{min} and CW_{max} are the respective minimum and maximum values of the CW size.

Table 5.1: LTE LAA channel access priority class configurations

Channel access priority class (p)	m_p	$CW_{min,p}$	$CW_{max,p}$	$T_{m\,cot,p}$	Allowed CW_p sizes
1	1	3	7	2 ms	3,7
2	1	7	15	3 ms	7,15
3	3	15	63	8 or 10 ms	15,31,63
4	7	15	1023	8 or 10 ms	15,31,63,127,255,511,1023

From the table, it can be seen that each priority class uses different $T_{m\,cot,p}$ that refers to the maximum channel occupancy time for the specific class p. According to the standard, for the priority classes 3 and 4, the $T_{m\,cot,p}$ equals to 10 ms if the absence of any other co-located unlicensed technology sharing the same spectrum band can be guaranteed on a long term basis. In a different case, it is limited to

8 ms. An eNB cannot continuously transmit in unlicensed spectrum for a period longer than $T_{m\,cot,p}$. After the end of the $T_{m\,cot,p}$, it must perform a CCA procedure to estimate again the occupancy of the channel.

On the other hand, in traditional Wi-Fi network without frame aggregation, an AP or a Station (STA) transmits only one packet after it successfully estimates the medium as idle. Such a Wi-Fi packet transmission typically lasts a few hundreds of μs. After the transmission of the packet, it has to compete again to access the medium against other co-located networks by performing a CCA procedure. In several still widely used Wi-Fi standards such as 802.11a/g frame aggregation is not supported. Even if frame aggregation is available (e.g. 802.11n/ac [27]), often it is not used depending on the traffic type (e.g. low latency constraints) [28].

It is clear that the transmission durations of LTE LAA and Wi-Fi are not balanced as the TXOP duration of LTE LAA is significantly longer compared to a single packet transmission of Wi-Fi. Moreover, as both networks perform an exponential backoff after they sense the channel as busy, it is possible for an LTE LAA network to gain consecutive times access to the channel forcing Wi-Fi to postpone its transmission for even longer period of time. This can lead to unfair coexistence between co-located LTE and Wi-Fi networks. Especially in the case of multiple LTE LAA networks, a co-located Wi-Fi network will be impacted drastically as it has to compete against more networks that are able to gain access to the channel for considerably longer duration.

In order to deal with this serious concern, we propose a new adaptive channel access scheme for LTE-U. According to this scheme, LTE has to perform a CCA before a transmission. If the CCA estimates the channel as idle, then the LTE LAA eNB transmits for a variable duration called TXOP in a range of 2 ms up to 20 ms. This TXOP is followed by a variable muting period in a range of 0 ms up to 20 ms. During the muting period, the LTE-U network that has finished a transmission of a TXOP duration has to remain silent in order to give channel access opportunities to other co-located networks (e.g. Wi-Fi or another LTE-U). After the end of the muting period (or at the end of the TXOP in case of zero muting period), the eNB has to perform again a CCA procedure before a new TXOP. In this solution, the introduction of the muting period can cause problems for delay sensitive traffic. In this case, similar to LTE LAA, a primary cell operating in licensed spectrum can still be used for time sensitive transmissions. In the rest of the article, we will refer to the proposed scheme as muting LTE-U (mLTE-U). Fig. 5.1 illustrates the proposed scheme.

This scheme can offer high coexistence flexibility as the mLTE-U behaviour can be adapted based on various parameters, such as the number and the type of the co-located networks, the Quality of Service (QoS) requirements that a network has to serve (e.g. best effort traffic, video traffic, etc.) and the load of the different networks. For instance, when an mLTE-U network coexists with multiple Wi-Fi

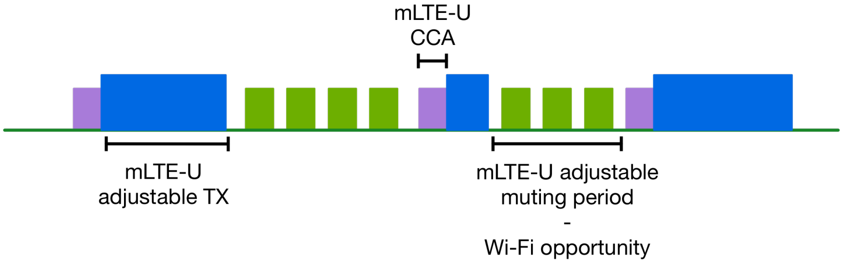

Figure 5.1: The design of the proposed mLTE-U scheme

networks, then the proposed scheme has to be adapted so that mLTE-U transmits using a short TXOP followed by a relatively long muting period. The Wi-Fi networks can exploit this period to further gain channel access. According to another example-scenario, an mLTE-U that serves a video streaming coexists with a Wi-Fi network that serves best-effort traffic. In this case, the mLTE-U transmission scheme has to be modified in order to use a higher TXOP followed by a shorter muting period for Wi-Fi transmissions.

5.5 Fairness in unlicensed spectrum

The purpose of the proposed scheme is to enhance the coexistence and increase the fairness among the co-located LTE-U and Wi-Fi networks. A fair coexistence scheme should offer all the available networks equal opportunities to the medium. It is important to point out the difference between fairness among different available technologies and fairness among the different coexisting networks, as it is depicted in Fig. 5.2.

According to the first approach (Fig. 5.2(a)), the wireless resources are divided among the co-located networks according to the different wireless technologies that are used. Hence, in the case of two coexisting wireless technologies such as LTE and Wi-Fi, half of the time the medium is used by LTE and half of the time is used by Wi-Fi. In our opinion, such an approach is not always fair as it does not take into consideration the number of the LTE and Wi-Fi networks respectively. For instance, if there are multiple co-located Wi-Fi networks and one LTE-U network, it would not be fair to Wi-Fi to split the time that the different technologies access the channel to the half.

Regarding the second approach (Fig. 5.2(b)), the medium is shared according to the number of the co-located networks in a technology-agnostic manner. Consequently, a coexistence mechanism that belongs in this category does not discriminate the coexisting networks based on the type of the wireless technology that they use. Instead, the distribution of the resources is done based on the number of

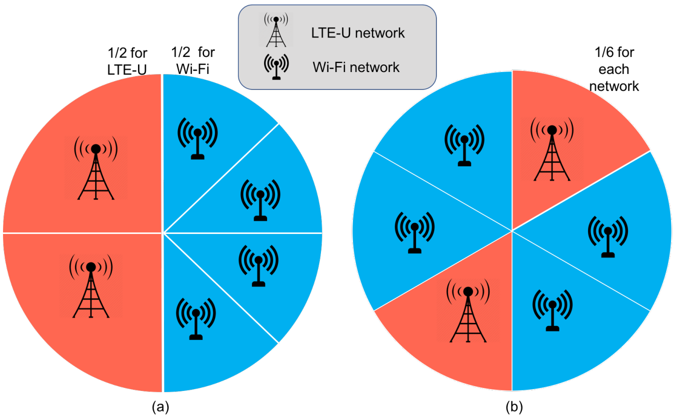

Figure 5.2: Spectrum sharing between different co-located technologies. a) spectrum sharing based on the different technologies b) Spectrum sharing in technology-agnostic way

the co-located networks and ideally based on several characteristics, such as the type and the amount of traffic that must be served.

In an ideal scenario in which all the different networks are aware of the requirements of each other and can exchange information, or a central coordinator is in charge of communicating with each network, collecting their traffic requirements and coordinating their transmissions, the distribution of the wireless resources could be done in a really fair manner.

However, in the wireless world, several diverse networks that have been designed, each having completely different principles in order to serve different requirements, are forced to coexist and compete for the wireless resources. Furthermore, the channel access mechanisms used by different technologies vary significantly among each other. Even between nodes of the same wireless technology equally time sharing of the wireless resources is not guaranteed. Wi-Fi is an indicative example of such a scenario. One of the basic principles of traditional Wi-Fi (without frame aggregation) is the equal division of the channel between the users. Hence, only one packet is transmitted by each node after the medium is sensed as idle. Nevertheless, very often there is a case in which a node faces better channel quality than another. Thus, the node with better channel conditions can perform a faster transmission, using a high Modulation and Coding Scheme (MCS) profile compared to the other. This way the node with the lower MCS profile occupies the channel for longer duration to transmit exactly the same number of bytes.

In the case of LTE and Wi-Fi coexistence, the two technologies that compete for the wireless resources are diverse having major design differences. The obtained throughput together with the channel occupancy are good indicators for the fairness that a coexistence technique can offer. Hence, in the rest of the article, the obtained throughput and the channel occupancy are adopted as key performance indicators for the evaluation of the proposed scheme. Towards a fair coexistence in line with the second approach that discussed above, the parameters of mLTE-U are selected in such a way that each participating network can achieve an equal ratio of throughput, compared to the maximum throughput that it can be achieved during the standalone operation.

5.6 Simulation environment

In order to evaluate the proposed scheme, experiments have been performed using the NS3 network simulator, which is an event-based and flexible simulation platform. The simulator allows the design of scenarios in which multiple LTE networks can coexist together with multiple Wi-Fi networks in the unlicensed spectrum. The LTE and Wi-Fi networks are able to operate using the same channel and can interfere with each other.

During the experiments, the LTE has been set to operate in the 5 GHz unlicensed band. As it is mentioned in Section 5.4, mLTE-U can transmit using a variable TXOP period, which ranges from 2 ms up to 20 ms. In addition, a muting period has been introduced to the LTE channel access scheme. This muting period ranges from 0 ms up to 20 ms and starts after the completion of a TXOP period. The maximum duration of both TXOP and muting period can be set to even higher values. However, we believe that this range is long enough to showcase the effect that the proposed scheme can have on the coexistence between mLTE-U and Wi-Fi networks in unlicensed spectrum.

Before an mLTE-U node starts a transmission, it has to complete a CCA procedure. The CCA parameters have been configured in order to be similar to the Wi-Fi LBT Category 4 procedure. Table 5.2 summarizes the specific mLTE-U parameters that have been used.

Regarding the Wi-Fi network, 802.11n mode has been selected in order to allow operation in 5 GHz unlicensed band. Additionally, frame aggregation is disabled so that we can investigate the traditional 802.11 transmission, according to which a single packet is transmitted after the channel is estimated as idle. Additionally, the network is configured to operate in SISO mode, so that the Wi-Fi operation can be comparable to other popular 802.11 standards that does not support MIMO mode such as 802.11a/g. Table 5.3 lists all the related parameters that have been used for the configuration of the Wi-Fi network. The common simulator parameters are presented in Table 5.4.

Before the beginning of a transmission burst mLTE-U must perform a CCA procedure. This means that the medium can be sensed as idle at any time. On the other hand, LTE is a scheduled technology and the scheduling is performed by the

Table 5.2: mLTE-U simulation parameters

Parameter	Value
Base station type	femtocell
Bandwidth	20 MHz
Defer period	34 μs
Slot duration	9 μs
$\mathrm{CW}_{\mathrm{min}}$	15
$\mathrm{CW}_{\mathrm{max}}$	1023
TXOP	2-20 ms
Muting period	0-20 ms
ED threshold	-62.0 dBm
CW update rule	80% NACKS
MIMO format	MIMO

eNB on a sub-frame level, meaning that each 1 ms the assignment of the wireless resources to the active UE can change. Hence, as every data transfer starts at the subframe boundaries, an LTE reservation signal is used after the channel is sensed as idle and until the beginning of the next subframe in order to preserve the channel and force other nodes to backoff. Fig. 5.3 illustrates the usage of the reservation signal. In the best-case but very rare scenario in which the channel is estimated as idle in the beginning of a subframe, the transmission of a reservation signal is not necessary and thus it is omitted. Contrariwise, when the channel is sensed idle immediately after the beginning of a subframe, then the reservation signal lasts for the rest of the subframe and the data transmission starts at the beginning of the next subframe. The duration of the reservation signal is deducted from the TXOP duration of the mLTE-U. For this reason, the minimum examined TXOP is 2 ms.

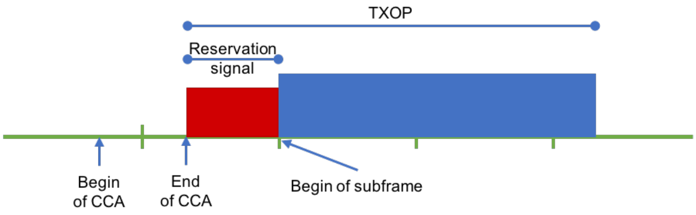

Figure 5.3: mLTE-U reservation signal

Table 5.3: Wi-Fi simulation parameters

Parameter	Value
Wi-Fi mode	802.11n
Frame aggregation	disabled
Bandwidth	20 MHz
DIFS duration	34 μs
Slot duration	9 μs
CW_{min}	15
CW_{max}	1023
ED threshold	-62.0 dBm
CS threshold	-82.0 dBm
RTS/CTS	disabled
MIMO format	SISO

5.7 Simulation scenarios

In order to verify the coexistence issue that occurs when LTE LAA operates next to Wi-Fi, a related simulation scenario has been designed. According to this scenario, an LTE LAA network consisting of one eNB and one UE operates in the proximity of a Wi-Fi network that consist of one AP and one STA.

Towards the performance evaluation of the proposed scheme, various simulation scenarios have been designed. For each scenario, all the different combinations of TXOP and muting values have been tested. For both mLTE-U and Wi-Fi networks, we assume that one end-device is connected to one base station. In each network, high load UDP traffic is transmitted in the DL, meaning from the eNB to the UE for LTE and from the AP to the STA for Wi-Fi.

For the evaluation of the proposed scheme during the first four scenarios, the mobility of the end-nodes is not taken into consideration. In these scenarios, we study the performance of the mLTE-U scheme in cases of different mLTE-U and Wi-Fi network densities. The first examined scenario consists of one mLTE-U network and one Wi-Fi network. The distance between the LTE eNB and the Wi-Fi AP is 10 meters, while the LTE UE and the Wi-Fi STA are located at a distance of 10 meters from the eNB and the AP respectively. In the remainder of the article we refer to this scenario as reference scenario. For the other investigated static scenarios, the number of the mLTE-U and Wi-Fi networks ranges from one up to

Table 5.4: Common simulation parameters

Parameter	Value
Simulation time per mLTE-U configuration	10 s
Traffic direction	Downlink
Traffic protocol	UDP
UDP payload size	1472 bytes
Radio propagation model	Log-distance path loss
Antenna pattern	omni-directional
TX power (eNB, AP)	18 dBm
TX power (UE, STA)	18 dBm

four networks for each type of technology. This way, various situations of high interest can be studied, such as:

- Coexistence of low mLTE-U and Wi-Fi density (e.g. reference scenario)
- Coexistence of high mLTE-U density and low Wi-Fi density (e.g. 4 mLTE-U and 1 Wi-Fi)
- Coexistence of low mLTE-U density and high Wi-Fi density (e.g. 1 mLTE-U and 4 Wi-Fi)
- Coexistence of both high mLTE-U and Wi-Fi density (e.g. 4 mLTE-U and 4 Wi-Fi)

In every scenario with multiple mLTE-U and/or multiple Wi-Fi networks, all the available nodes (eNBs, UEs, APs and STAs) are deployed randomly in the proximity of each other (within 20 meters). This way, the ED threshold is surpassed and the backoff mechanism of mLTE-U and Wi-Fi is triggered during every transmission. Fig. 5.4 presents the investigated static coexistence scenarios.

Furthermore, the effect of mobility in the coexistence of mLTE-U and Wi-Fi is studied in an indicative mobile scenario. During the mobile scenario and similar to the reference scenario, one mLTE-U network, consisting of one eNB and one UE, coexists with one Wi-Fi network consisting of one AP and one STA. The UE is placed at a distance of 25 meters from the eNB and the STA is placed at a distance of 100 meters from the AP. During the execution of the scenario, the UE moves away from the eNB, while the STA moves towards the AP. The above described scenario is depicted in Fig. 5.5.

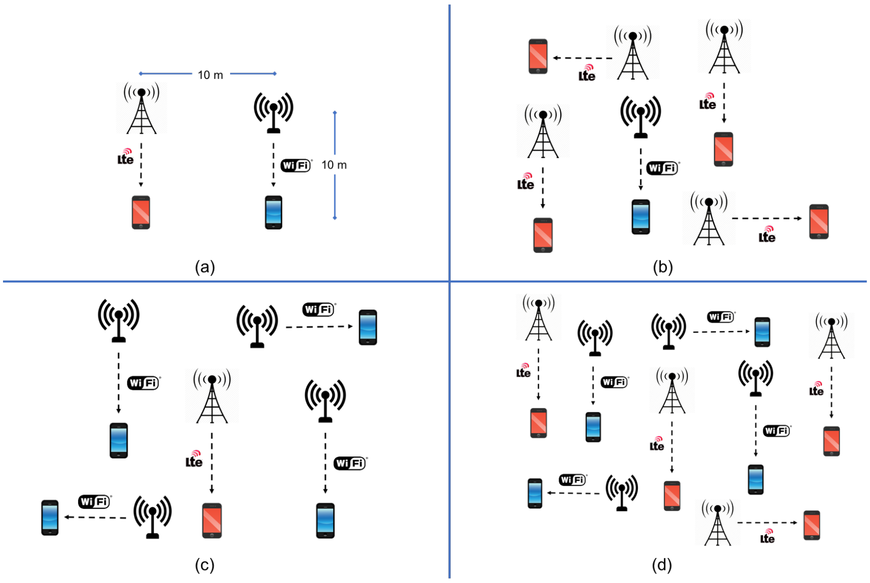

Figure 5.4: Investigated static coexistence scenarios. a) Reference scenario b) Dense mLTE-U deployment scenario c) Dense Wi-Fi deployment scenario d) Dense mLTE-U and Wi-Fi deployment scenario

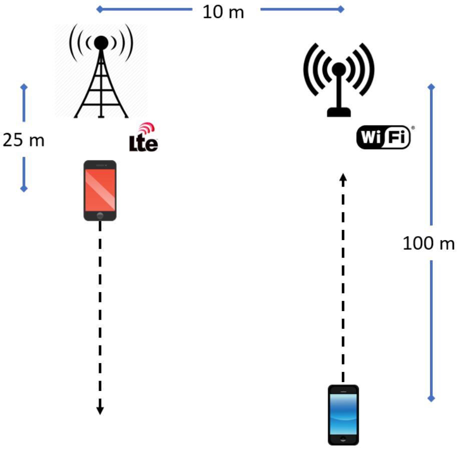

Figure 5.5: Mobile coexistence scenario

5.8 Performance evaluation

5.8.1 LTE LAA and Wi-Fi coexistence evaluation

In Section 5.4, we discussed the coexistence problems that can arise when an LTE LAA network operates next to a Wi-Fi network in the unlicensed spectrum. This section, evaluates the impact of the different LTE LAA priority classes (Table 5.1) on the performance of Wi-Fi.

Fig. 5.6 showcases the CCA procedure of LTE LAA that is configured to use priority class 3. The upper part of the figure shows the CCA procedure, when LTE LAA is the only network in the unlicensed channel, while the lower part shows the procedure when LTE LAA coexists with a Wi-Fi network. The notations of the LTE LAA CCA procedure are specified in Table 5.5.

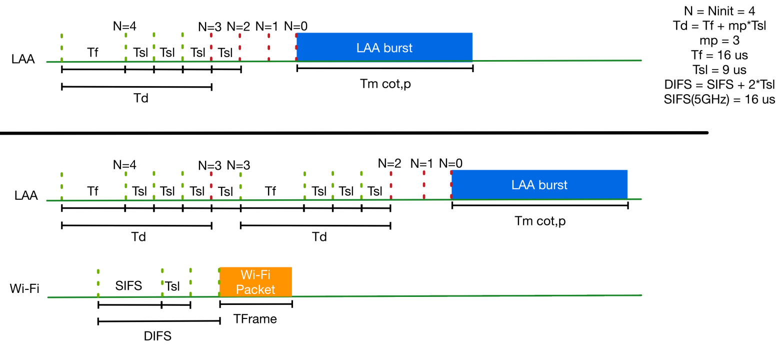

Figure 5.6: LTE LAA CCA procedure

According to the LTE LAA standard, an LTE LAA transmission is performed, after the channel is sensed as idle during all the slots of a defer period (T_d) and after the backoff counter (N) is reached zero. A defer period consists of a silent period (T_f), followed by m_p slots of T_{sl} duration. The number of slots (m_p) is defined by the priority classes. An LTE LAA node that wants to transmit, first senses the medium for a defer period ($T_d = T_f + m_p * T_{sl}$) and then, it always performs an exponential backoff. The backoff counter N is chosen randomly in a range of $0 \leq N \leq CW$. In the beginning, the CW is initialized to the $CW_{min,p}$ value specified by the corresponding priority class. If during the backoff procedure the channel is sensed as busy, then the backoff counter freezes. The channel is reported as busy, when the sensed energy during a CCA slot is above the ED threshold. Every time the channel is sensed as busy, the LTE LAA node has to sense again for an idle defer period (T_d) and then it continues decreasing the backoff counter from the point it stopped. This is depicted in the second half of the Fig. 5.6, where a Wi-Fi transmission occurs during the backoff procedure of LAA.

Table 5.5: Notations of the LTE LAA and Wi-Fi CCA procedure

Parameter	Meaning
N	Backoff counter
T_d	The defer duration
T_f	The silent period in the beginning of T_d
m_p	Number of backoff slots
T_{sl}	Backoff slot duration
$T_{mcot,p}$	LTE transmission duration
T_{Frame}	Wi-Fi frame transmission duration
SIFS	802.11 Short Interframe Space
DIFS	802.11 DCF Interframe Space

The value of the CW is adjusted based on the HARQ feedback from the UEs. If the feedback indicates that at least 80% of the HARQ-ACK values, corresponding to the most resent DL transmission burst were erroneous (negative acknowledgments, NACKS), for example when a lot of collisions occur, then the CW is doubled for the next CCA procedure. This can happen until the CW reaches a maximum value $CW_{max,p}$ specified by each priority class. If less than 80% of the HARQ-ACK values are determined as NACK, the CW is reset to the minimum value.

In order to assess the coexistence offered by LTE LAA to a co-located Wi-Fi network, all the four priority classes have been tested via the simulation platform. The simulation platform has been modified in order to enable LTE LAA simulation. To this end, the defer period, the $\mathrm{CW_{min}}$, the $\mathrm{CW_{max}}$ and the TXOP have been adjusted to the corresponding values specified by each priority class. The Wi-Fi simulation parameters are the same as listed in Table 5.3. For all the four priority classes, the distance between the eNB and the AP is 10 meters and the distance between each base station with its respective end-device is 10 meters. High UDP traffic of 200 Mbps is transmitted on the DL in both networks. Fig. 5.7 presents the obtained throughput for LTE LAA and Wi-Fi (vertical axis) according to the corresponding LTE LAA priority class (horizontal axis). The Wi-Fi throughput in standalone operation (without LTE LAA interference) is also presented as a reference point.

From the graph, it can be seen that LTE LAA has a big impact on the performance of Wi-Fi. For the two higher priority classes, LTE LAA has priority over Wi-Fi due to the differences in the configuration of the channel estimation proce-

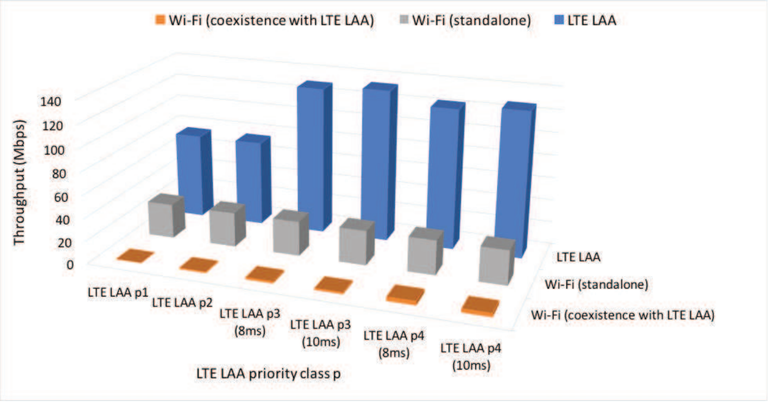

Figure 5.7: LTE LAA and impact on Wi-Fi throughput for different channel access priority classes

dure that the two networks use. Wi-Fi uses always a DIFS period of 34 μs, while the $\mathrm{CW_{min}}$ and $\mathrm{CW_{max}}$ values are 15 and 1023 respectively. On the other hand, LTE LAA uses a short defer period ($\mathrm{T_d}$) and shorter ranges for the selection of the CW (Table 5.1). Regarding the two lower priority classes the configurations of the channel estimation procedure are more in line with the Wi-Fi LBT procedure. Nevertheless, LTE LAA uses transmission bursts ($\mathrm{T_{m\ cot,p}}$) of significant longer duration (8ms or 10ms) compared to a typical Wi-Fi packet transmission that lasts some hundreds of μs. Hence, Wi-Fi is able to achieve a maximum throughput of 3.32 Mbps when LTE LAA is configured with the lowest priority class and uses the shorter possible transmission burst (8 ms). However, the obtained throughput is significantly lower compared to the throughput that Wi-Fi can achieve in a standalone operation (30.44 Mbps).

The graph also showcases that the different priority classes have an effect on the LTE LAA throughput. According to the two higher priority classes, LTE LAA transmits for 2 ms and 3 ms respectively before it estimates the channel again. On the contrary, according to the two lower priority classes, LTE LAA transmits for 8 or 10 ms after a successful CCA procedure. This means that for the higher classes it performs a CCA procedure more often than for the lower. As a result, it spends more time assessing the channel and this has an immediate effect on the obtained throughput.

In every case, the simulation results show that LTE LAA can degrade the performance of Wi-Fi in its classic form, meaning that no frame aggregation is used and it transmits one packet every time the medium is sensed as idle. In the rest of this section, we evaluate the performance of the proposed mLTE-U scheme under different scenarios and we discuss what configurations of TXOP and muting period can offer fair coexistence for each scenario.

5.8.2 Standalone scenario evaluation

In this section, the performance of both mLTE-U and Wi-Fi networks is evaluated in standalone case. In this scenario, the networks are located away from each other and operate independently, having full access to the channel. The distance between the networks is set to 1000 meters and both systems are offered an equal UDP load of 200 Mbps.

Fig. 5.8 shows the obtained DL throughput results of mLTE-U network. On the x-axis are the configurations of muting period duration in ms ranging from 0 up to 20. On the z-axis are the different TXOP configurations in ms ranging from 2 up to 20. Finally, on the y-axis are the DL throughput values in Mbps for every combination of TXOP and muting period durations. As it can be observed and according to the expectations, the introduction of the muting period has an impact on the maximum throughput that can be achieved by mLTE-U.

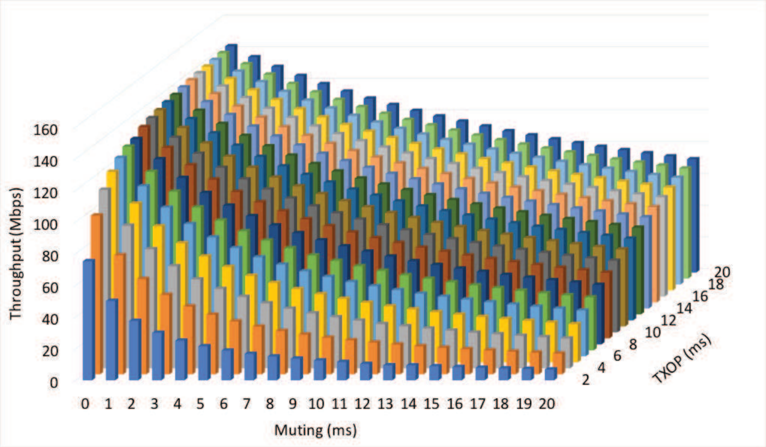

Figure 5.8: Obtained mLTE-U throughput during the standalone scenario

This graph shows clearly how the mLTE-U throughput drops as the TXOP period decreases and the muting period increases. Hence the minimum throughput value corresponds to a configuration in which TXOP lasts for 2 ms and is followed by a muting period that lasts 20 ms. Respectively, the maximum throughput value corresponds to a TXOP of 20 ms followed by a muting period of 0 ms. The difference between the maximum and the minimum value of the DL throughput reaches 95.2%.

Fig. 5.9 shows the DL throughput diagrams of mLTE-U and Wi-Fi, when the mLTE-U muting period is zero and the mLTE-U TXOP period varies from 2 to 20 ms. When the muting period is zero the mLTE-U can reach the maximum throughput for each corresponding TXOP.

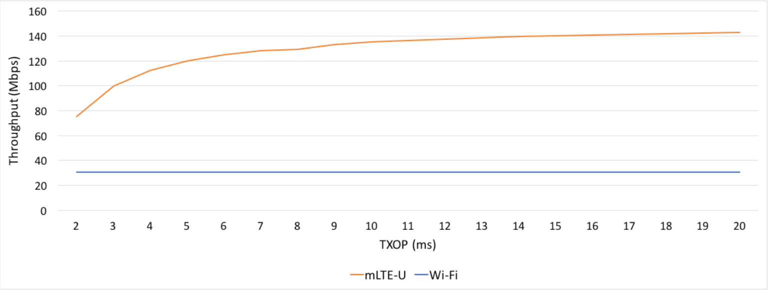

Figure 5.9: Standalone mLTE-U and Wi-Fi throughput for different TXOP without muting period

As can be seen from the graph, the Wi-Fi throughput remains constant at 30.44 Mbps. This is to be expected as the Wi-Fi network is not in the proximity of mLTE-U and thus it is not affected by its transmissions. On the contrary, the mLTE-U throughput ranges from 75.18 up to 142.81 Mbps. This variation is related to the configured TXOP duration of the mLTE-U. As the TXOP duration decreases, the mLTE-U has to perform more often a CCA procedure in order to evaluate the status of the channel. This has a significant impact on channel utilization and respectively on the obtained throughput. For a lower TXOP duration the eNB spends more time evaluating the channel compared to the scenario in which it is configured with a higher TXOP duration.

This becomes clearer by comparing two different mLTE-U configurations for the standalone scenario. For both configurations, DL traffic is transmitted for 10 seconds. According to the first configuration, the eNB transmits for a TXOP of 20 ms and each TXOP is followed by a muting period of 20 ms. Hence, it evaluates the channel every 40 ms. This means that the total number of CCA performed during the whole experiment is 10000 ms / 40 ms = 250 channel evaluations. When the eNB transmits for a TXOP of 4 ms followed by a muting period of 4 ms, then the channel is sensed every 8 ms. This corresponds to 10000 ms / 8 ms = 1250 channel evaluations.

Another parameter of high interest that is closely related to the obtained throughput is the channel occupancy time. The obtained simulation results show that during the standalone operation, Wi-Fi occupies the channel for 70.10% of the time. This means that Wi-Fi spends a high percentage of time sensing the medium. On the other hand, in the proposed scheme mLTE-U achieves the highest channel occupancy when the muting period is configured to be zero. In that case, mLTE-U competes for the medium immediately after the end of the TXOP. Fig. 5.10 shows the percentage of channel occupancy for both Wi-Fi and mLTE-U for every TXOP duration and for muting period equal to zero.

As it has been discussed above, the TXOP duration is closely related to the

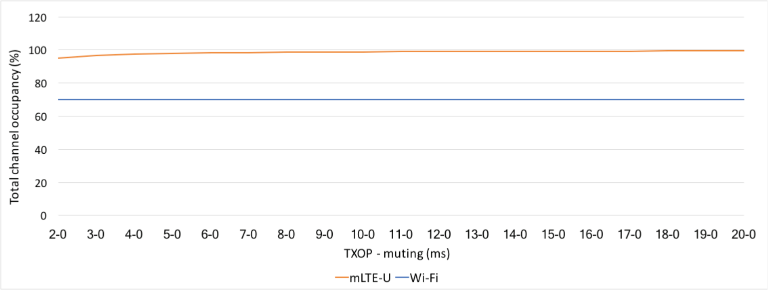

Figure 5.10: Channel occupancy of mLTE-U and Wi-Fi during the standalone scenario

frequency of CCA procedure. As it is illustrated in Fig. 5.10, for the lower values of TXOP the CCA frequency has a small impact on the channel occupancy of CCA. It must be noted that the transmission of the mLTE-U reservation signal is counted in the computation of the channel occupancy. However, the transmission of the reservation signal is not taken into account for the computation of the obtained throughput. For this reason, the throughput drop that can be observed in Fig. 5.9 for lower TXOP is not reflected in the achieved mLTE-U channel occupancy that is depicted in Fig. 5.10. Furthermore, this figure showcases the high spectral efficiency of LTE, especially in a clear environment. LTE can achieve high spectral efficiency as it is a scheduled technology that uses a centralized MAC protocol and was originally designed to operate in the licensed spectrum. During this standalone scenario, the percentage of the mLTE-U channel occupation ranges from 94.90% for 2 ms of TXOP duration up to 99.47% for 20 ms of TXOP duration. The addition of the muting period following a TXOP can provide fairness among mLTE-U and Wi-Fi at the cost of decreasing the spectral efficiency and the throughput of mLTE-U. However, towards a fair coexistence between different technologies concessions must be made. Moreover, mLTE-U can use the licensed anchor to accomplish critical transmissions, such as the control signals or serve applications with high QoS requirements.

5.8.3 Reference scenario evaluation

The reference scenario is similar to the standalone scenario with the difference that the two networks are placed in the proximity of each other. Fig. 5.4a illustrates the reference scenario. In this scenario, the two networks have to compete for the medium before a transmission.

Fig. 5.11 shows the obtained DL throughput of the Wi-Fi network. The x-axis is the TXOP duration of mLTE-U in ms and the z-axis is the muting period of mLTE-U in ms. The y-axis shows the DL Wi-Fi throughput for each different combination of mLTE-U TXOP and muting period. Fig. 5.12 presents the DL

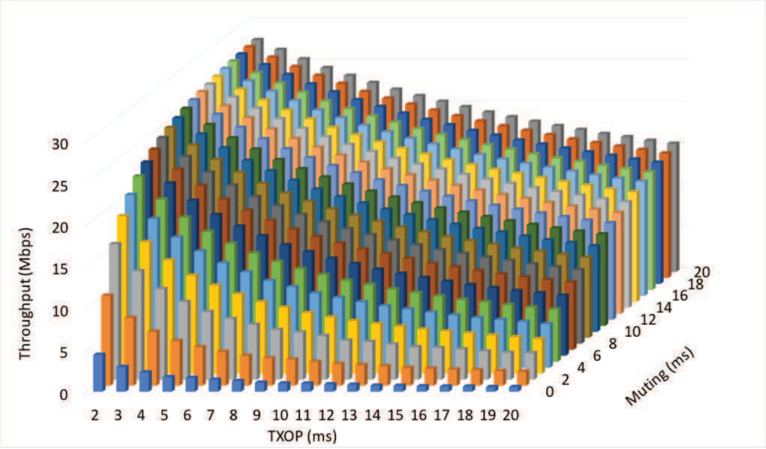

Figure 5.11: Wi-Fi throughput during the reference scenario

throughput of the mLTE-U network. In this diagram, the x and z axes are reversed compared to Wi-Fi. Hence the x-axis holds the muting period and the z-axis holds the TXOP duration of mLTE-U.

By observing the diagrams, it can be seen that they are inverse of each other. In case of Wi-Fi, the throughput increases as the muting period of mLTE-U increases. This is logical as highest mLTE-U muting period offers more opportunities to Wi-Fi to estimate the channel as idle and start a transmission. Furthermore, the Wi-Fi throughput is inversely proportional to the mLTE-U TXOP. As it is explained above, a shorter TXOP gives more often opportunities to Wi-Fi to compete for the medium and eventually gain access to the channel. On the contrary, similar to the standalone scenario the throughput of mLTE-U increases when the TXOP duration increases due to less often CCA procedure. Additionally, as it is expected, a shorter muting period offers higher throughput compared to a longer one.

Comparing the reference scenario with the standalone operation, it can be observed that during the reference scenario, the mLTE-U throughput is slightly lower (less than 2 Mbps of throughput drop). This is justified by the fact that in this scenario, the two networks compete for the channel access. As result, Wi-Fi can win several CCA battles. A Wi-Fi transmission typically lasts for few hundreds of μs. Hence, the impact of the Wi-Fi network on mLTE-U due to the CCA procedure is not so significant. On the other hand, the presence of the mLTE-U has an impact on Wi-Fi throughput compared to the standalone scenario where it was constantly nearly to 30 Mbps. The results show that the Wi-Fi throughput can drop to 0.56 Mbps in case that the eNB uses a TXOP of 20 ms and a muting period of 0. In this case mLTE-U occupies the channel for long time and competes for the medium immediately after the end of the TXOP. Thus, Wi-Fi transmits only when it wins

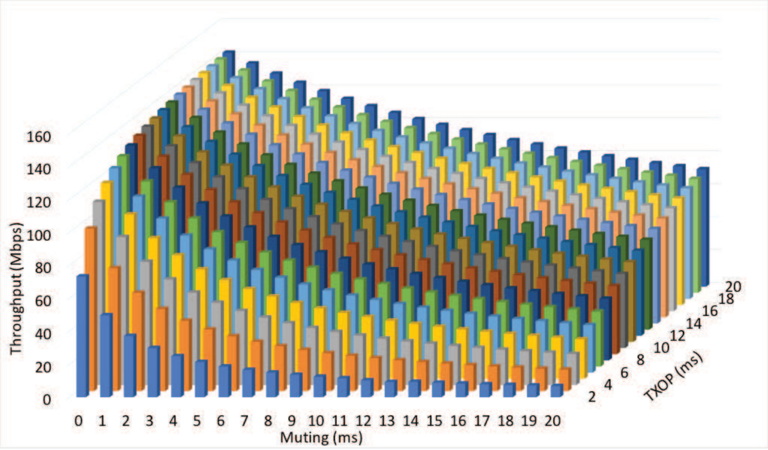

Figure 5.12: mLTE-U throughput during the reference scenario

the CCA battle. Accordingly, the Wi-Fi throughput reaches its peak, which is 27.80 Mbps, when the mLTE-U uses the longest muting period of 20 ms and the shortest TXOP of 2 ms. Then mLTE-U remains silent the most of the time and gains access for short TXOP. The difference between the maximum and minimum throughput corresponds to 97.99%.

As it has been discussed in Section 5.5, in order to share the channel in a fair manner, it must be ensured that all the co-located networks can gain equal opportunities to the medium. Regarding the reference scenario, it is expected that fair coexistence can be achieved when the mLTE-U network is configured with a TXOP and a muting period of the same duration. In Fig. 5.13 both the mLTE-U and the Wi-Fi throughput are depicted for every pair of TXOP and muting period of the same duration. Comparing this figure with Fig. 5.9, it can be observed that during the reference scenario, mLTE-U and Wi-Fi are able to achieve almost half of the throughput that could be reached during the standalone operation. Regarding the mLTE-U, for every pair of TXOP and muting period it achieves marginally lower throughput than the half of the standalone scenario. In the contrast, Wi-Fi obtains slightly higher throughput than the half that it can reach during the standalone operation. This is justified by the fact that the two networks compete for the channel access. mLTE-U transmits for a TXOP duration and then it remains silent for the same period of time. Wi-Fi can access the medium during this period that in a wider scale equals to the half duration of the experiment. Furthermore, Wi-Fi is possible to win multiple CCA battles. In this case, it can transmit a packet for each one of the idle channel assessments, gaining in total a slightly higher throughput than the half of the standalone operation. As result, mLTE-U throughput is limited marginally below the half of the standalone scenario.

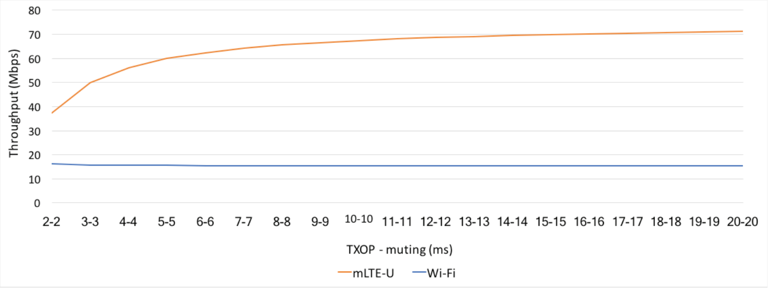

Figure 5.13: mLTE-U and Wi-Fi fair throughput during the reference scenario

The percentage of channel occupancy for both mLTE-U and Wi-Fi networks and for every pair of TXOP and muting period of the same duration are presented in Fig. 5.14. This graph points out the superiority of mLTE-U over Wi-Fi regarding the spectral efficiency. As the TXOP duration increases, the channel occupancy of mLTE-U increases, approaching the highest possible value of 50%. As the TXOP duration decreases, mLTE-U has to perform more often a CCA procedure. This decreases its spectral efficiency as more time is spent in estimating the channel conditions. Regarding Wi-Fi, its channel occupancy slightly increases as the TXOP of mLTE-U decreases. This is again related to the frequency of mLTE-U channel estimation. A high CCA frequency (low TXOP) increases the probabilities of Wi-Fi to win the channel and transmit, increasing this way its total channel occupancy.

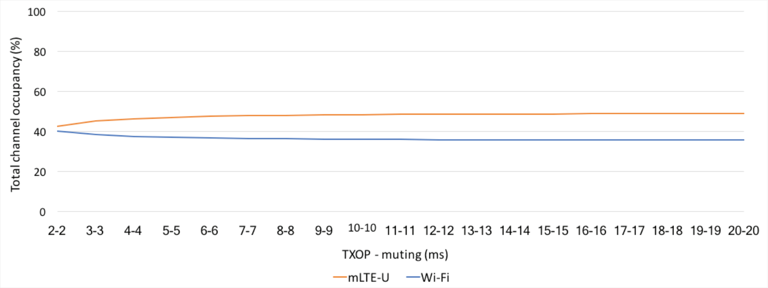

Figure 5.14: Channel occupancy of mLTE-U and Wi-Fi towards fair coexistence during the reference scenario

5.8.4 Dense mLTE-U deployment scenario evaluation

In this section, we evaluate the performance of the proposed scheme under a dense mLTE-U deployment scenario. In this scenario, one Wi-Fi and four mLTE-U networks operate in the proximity of each other. Fig. 5.4b illustrates the described scenario.

Fig. 5.15 and Fig. 5.16 present the obtained throughput of the Wi-Fi network and the combined throughput of the mLTE-U networks respectively. In this scenario, the Wi-Fi throughput is highly affected by the presence of the four mLTE-U networks.

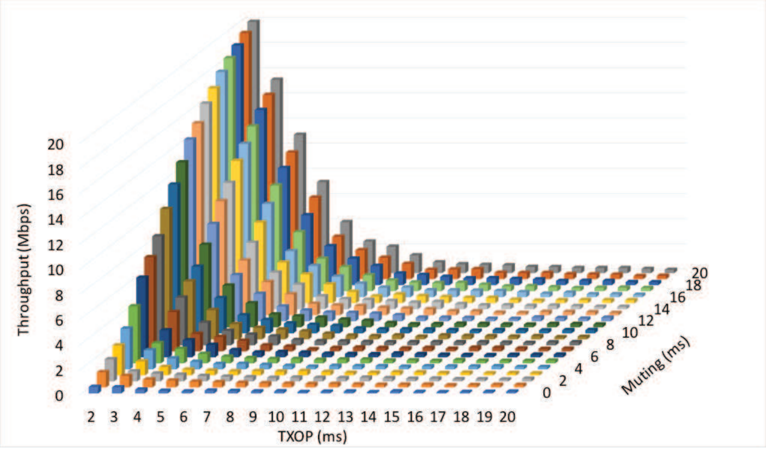

Figure 5.15: Wi-Fi throughput during the dense mLTE-U scenario

Under an mLTE-U dense deployment, the possibilities of a muting period to be exploited by another mLTE-U network are very high, especially when they are configured to use high TXOP duration and low muting period.

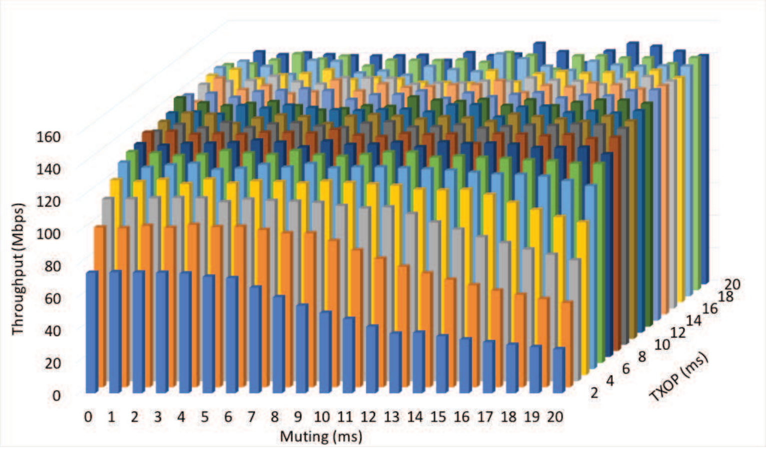

Figure 5.16: mLTE-U combined throughput during the dense mLTE-U scenario

In the contrary, when the mLTE-U networks are configured to use a short

TXOP and a high muting period, they remain silent simultaneously for a longer period of time. Wi-Fi can exploit these periods in order to transmit. Hence, the configuration of the highest muting period (20 ms) and the shortest TXOP (2 ms) offers the highest combined muting period (12 ms) for Wi-Fi. Then, Wi-Fi can achieve the highest throughput that corresponds to 19.96 Mbps. It worth to mention that this value is relatively higher than the achieved throughput during the reference scenario where the mLTE-U was configured with TXOP of 8 ms followed by a muting period of 12 ms, which was 18.46 Mbps. This difference can be explained by the possibility of multiple mLTE-U transmissions to start simultaneously meaning that more than one CW counters reached zero at the same time. In this situation, the multiple mLTE-U transmissions will interfere with each other, giving the same time higher combined muting period to Wi-Fi.

By the time a TXOP starts, the transmitting node does not sense the medium for other concurrent transmissions. When multiple mLTE-U nodes start transmitting simultaneously, the interference caused by longer TXOPs has bigger impact compared to the shorter ones. This is the reason that the combined throughput graph of mLTE-U fluctuates during the longer TXOPs. This observation is also valid for LTE LAA operation and especially for lower priority classes that the duration of the transmission burst is longer.

Mechanisms that are able to deal with the interference between multiple mLTE-U transmissions are required. According to a possible solution, the transmitting node could periodically (e.g. every 2 ms) pause its transmission in order to sense the medium for other potential transmissions for a short period of time (e.g. a defer period of 16 μs). If during this period the medium is idle, then it continues its transmission without performing a backoff. Otherwise, if the medium is busy, it can postpone its transmission and perform a CCA procedure. Techniques such as enhanced Inter-Cell Interference Coordination (eICIC) [29] that is designed to mitigate intra-frequency interference could be also part of the solution. Further study of interference management between different mLTE-U nodes is not in the scope of this article and is considered as future work.

In order to achieve fair coexistence between the different co-located mLTE-U and Wi-Fi networks, the wireless resources must be equally distributed between them. When fairness is considered in terms of throughput, each one of the five networks must be able to obtain 20% of the throughput that can be achieved in the standalone scenario. This corresponds to 6.09 Mbps for Wi-Fi and to 28.56 Mbps for each one of the mLTE-U networks (114.24 Mbps combined mLTE-U throughput). Hence, from all the possible configurations of TXOP and muting period must be chosen the ones that provide a throughput that approaches these values. Fig. 5.17 illustrates the Wi-Fi and the mLTE-U combined throughput for the configurations that can enable fair coexistence.

As can be observed, in this scenario mLTE-U can enable fair coexistence with

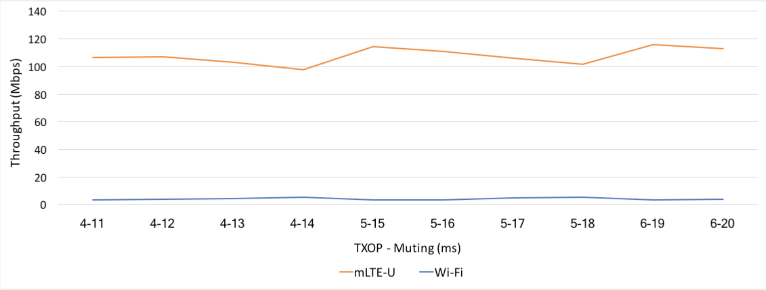

Figure 5.17: mLTE-U configurations that can enable fair coexistence with Wi-Fi during the dense mLTE-U scenario

Wi-Fi when it is configured with a relatively low TXOP followed by long muting period. This is something to be expected as from Fig. 5.15 is clear that for configurations of high TXOP followed by muting periods of varying duration, mLTE-U have a deep impact on Wi-Fi. As it has been discussed earlier, a long muting period in combination with a short TXOP offers to Wi-Fi more often a common muting slot, during which it can transmit.

5.8.5 Dense Wi-Fi deployment scenario evaluation

In this section, we study another scenario of high interest in which one mLTE-U network coexists with a dense Wi-Fi deployment consisting of four Wi-Fi networks. Fig. 5.4c illustrates the examined topology. Fig. 5.18 presents the combined throughput of Wi-Fi and Fig. 5.19 the obtained throughput of mLTE-U.

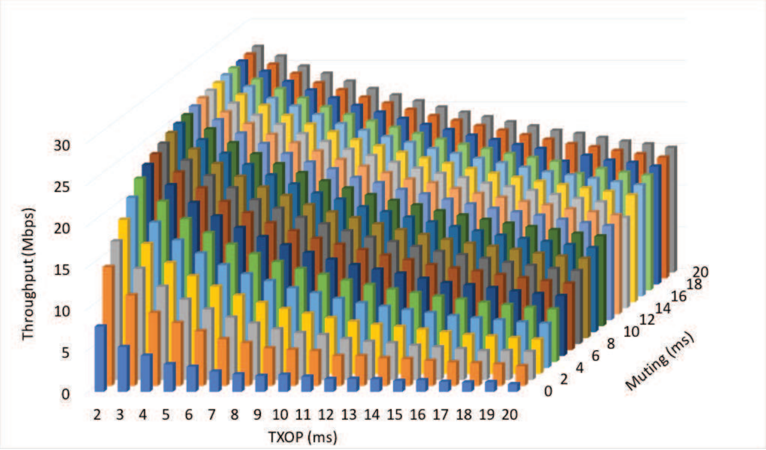

Figure 5.18: Wi-Fi combined throughput during the dense Wi-Fi scenario

As it can be observed, during this scenario Wi-Fi can achieve a combined throughput similar to the reference scenario. The maximum combined Wi-Fi throughput approaches the 27.12 Mbps. This value is slightly lower than the respectively value of the reference scenario (27.80 Mbps), due to the multiple Wi-Fi networks that compete to access the shared channel. As it is expected, this value is achieved when mLTE-U is configured with the lowest TXOP followed by the highest muting period.

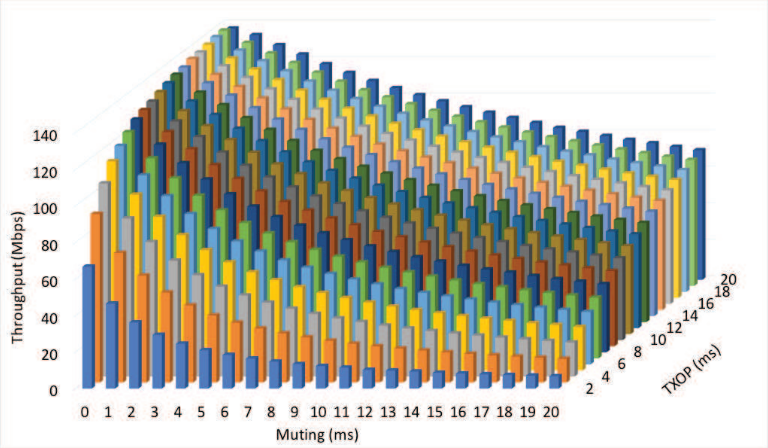

Figure 5.19: mLTE-U throughput during the dense Wi-Fi scenario

Similar to the dense mLTE-U deployment scenario, fair coexistence can be achieved when all the co-located networks have equal opportunities to the wireless resources. Consequently, each one of the five networks must be able to achieve 20% of the throughput that can be reached during the corresponding standalone scenario. This equals to 6.09 Mbps for each Wi-Fi network (24.36 Mbps combined Wi-Fi throughput) and to 28.56 Mbps for the mLTE-U network. Fig. 5.20 depicts the TXOP and muting period configurations that offer fair coexistence in terms of equivalent throughput ratio among the different networks.

The graph reveals that fair coexistence can be attained when relatively low TXOP durations are used. The corresponding muting period can be configured in a wider range of values. As only one mLTE-U network coexists with multiple Wi-Fi networks, a short TXOP can offer more often CCA opportunities and a muting period during which the Wi-Fi networks can compete for the medium.

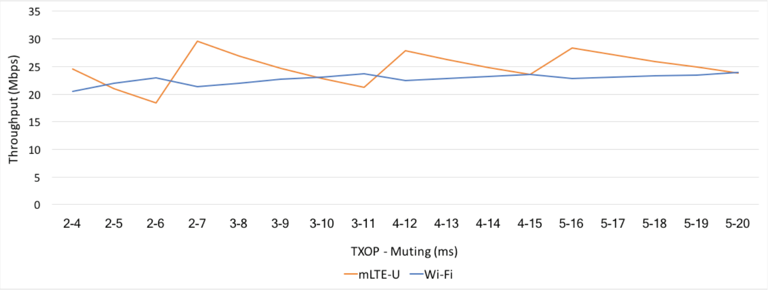

Figure 5.20: mLTE-U configurations that can enable fair coexistence with Wi-Fi during the dense Wi-Fi scenario

5.8.6 Dense mLTE-U and Wi-Fi deployment scenario evaluation

This section showcases the performance of the proposed scheme under both dense mLTE-U and Wi-Fi deployment scenario. As it is presented in Fig. 5.4d, this scenario consists of four mLTE-U networks and four Wi-Fi networks. Each network is in the proximity of the others.

The combined throughput of Wi-Fi and of mLTE-U are shown in Fig. 5.21 and Fig. 5.22 respectively.

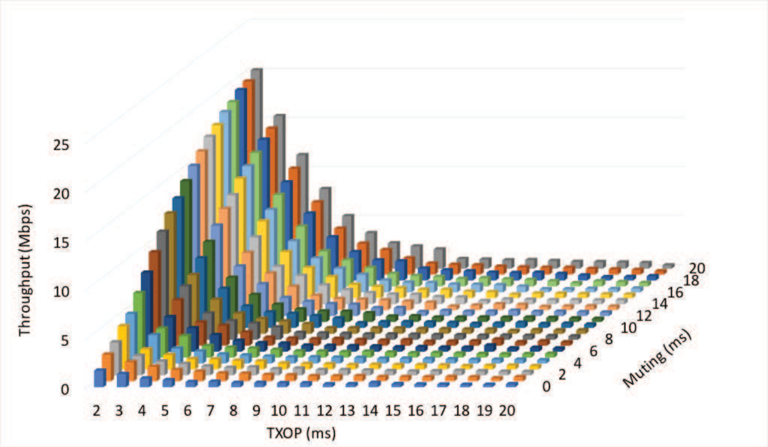

Figure 5.21: Wi-Fi combined throughput during the dense mLTE-U and dense Wi-Fi scenario

Fig. 5.21 indicates that the Wi-Fi networks are clearly impacted by the coexisting mLTE-U networks in the majority of the configurations. However, when mLTE-U is configured with short TXOP and relatively long muting period durations the combined Wi-Fi throughput is significantly improved. The maximum combined throughput of Wi-Fi reaches 20.20 Mbps and it corresponds to 66.36% of the throughput that a Wi-Fi network can achieve during the standalone scenario. The multiple mLTE-U networks competing for the medium offer limited opportunities to Wi-Fi similarly to the scenario described in Section 5.8.4. In addition, due to the presence of multiple Wi-Fi networks the exploitation of these opportunities becomes even less optimal as they compete among each other to access the channel. On the other hand, the mLTE-U networks achieve a maximum combined throughput that approaches the throughput that it can be reached in the standalone case.

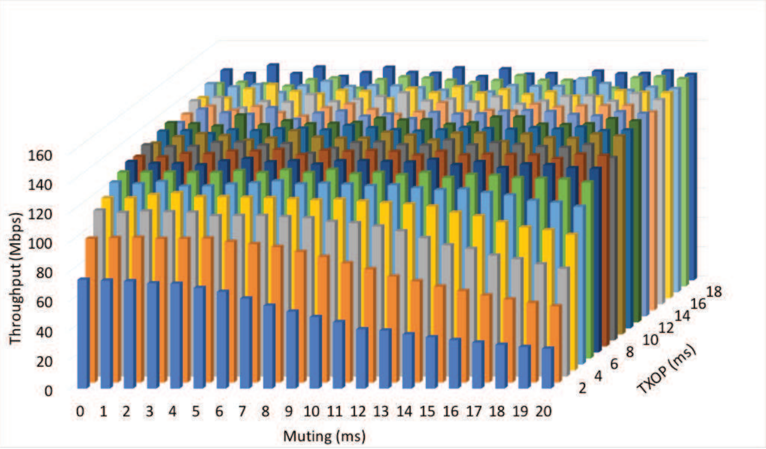

Figure 5.22: mLTE-U combined throughput during the dense mLTE-U and dense Wi-Fi scenario

Towards a fair coexistence, the selection of TXOP and muting period must be done in a way that all the co-located networks are able to reach the 1/8 of the respective throughput of the standalone scenario. This means that each mLTE-U network must be able to achieve a maximum of 17.75 Mbps, while each Wi-Fi network must be able to reach around 3.75 Mbps. In terms of combined throughput mLTE-U should obtain 71.4 Mbps and Wi-Fi should be able to reach 15.2 Mbps. Fig. 5.23 shows the TXOP and muting period values that can offer throughput that approaches the desired values for both mLTE-U and Wi-Fi.

As can be seen from the graph, fair coexistence can be achieved when the mLTE-U networks are configured with relatively low TXOP duration values. These TXOP values are followed by a muting period that varies from average to higher values as the TXOP increases. In this dense scenario, the selected values give short TXOP to mLTE-U followed by longer muting period during which the Wi-Fi networks compete and access the medium.

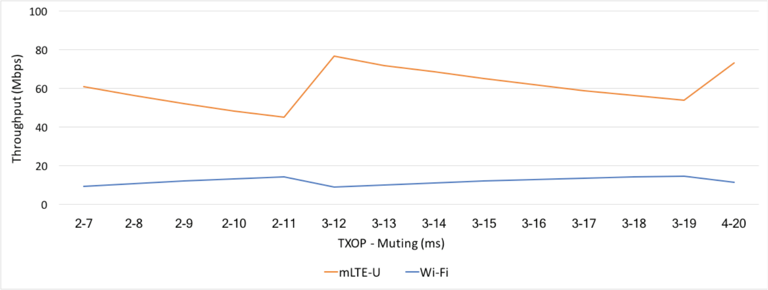

Figure 5.23: mLTE-U configurations that can enable fair coexistence with Wi-Fi during the dense mLTE-U and Wi-Fi scenario

5.8.7 mLTE-U and Wi-Fi mobile scenario evaluation

In the previous described scenarios, all the end-devices (UE and STAs) were deployed statically, targeting to showcase the behavior of the proposed mLTE-U scheme in different density scenarios of high interest. This section discusses the effect of mobility when mLTE-U coexists with Wi-Fi. As illustrated in Fig. 5.5, one mLTE-U network coexists with one Wi-Fi network. The UE moves away from the eNB, while the STA moves towards the AP.

Fig. 5.24 and Fig. 5.25 show the channel occupancy of mLTE-U and Wi-Fi for the configurations of mLTE-U that can enable fair coexistence and for different distances of each end-device from the corresponding base station. The left part of the distance pairs represents the distance between the eNB and the UE, while the right part represents the distance between the AP and the STA. As can be seen from the graphs, the mLTE-U configurations that offer fairness are the same as the ones selected during the reference scenario (Section 5.8.3). These configurations correspond to the pairs, in which TXOP and muting period have equal duration.

In Fig. 5.24 can be seen that the channel occupancy of mLTE-U for the selected configurations ranges from 42.5% to 49.4%. The difference in the percentage of channel occupancy lies in the fact that as the TXOP duration decreases, mLTE-U has to perform more often a CCA procedure spending more time in estimating the channel. Hence, when a longer TXOP duration is used, the spectral occupancy is increased approaching the highest possible value of 50% for the case of two coexisting networks. In Fig. 5.25 can be observed that the channel occupancy of Wi-Fi increases for longer distances between the AP and the STA and decreases for smaller distances. As an end-device moves far away from the associated base station, a lower MCS profile is used to render the wireless link more robust and able to cope with the decreased channel quality. However, a lower MCS profile corresponds to an increased channel occupancy, as a transmission requires more time compared to the case when a higher MCS profile is used.

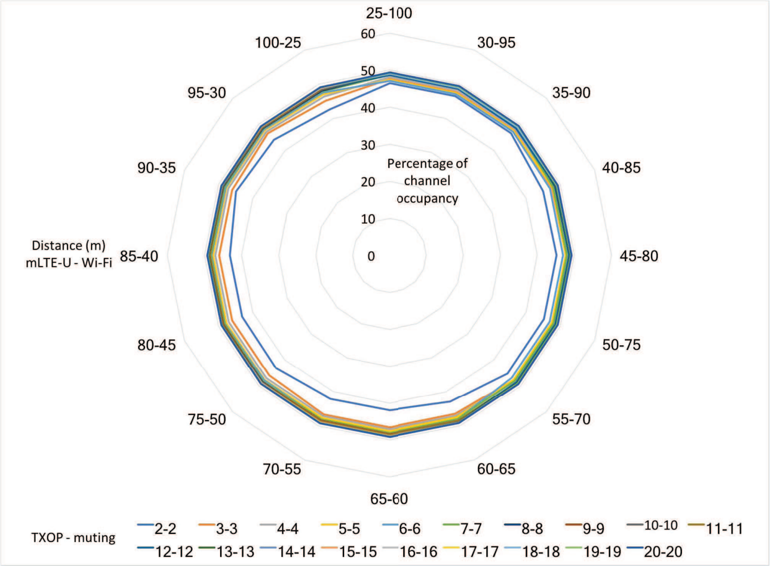

Figure 5.24: mLTE-U fair channel occupancy for different distances between the UE and the eNB and between the STA and the AP

As discussed in Section 5.5, fair coexistence refers to equal occupancy of the channel. Hence, for this definition of fairness and for the proposed coexistence scheme, the mobility of the end-devices does not affect the selection of the mLTE-U configurations that can enable fair sharing of the spectral resources.

5.9 Automatic fair parameter selection

In the previous sections, the proposed scheme has been evaluated for different scenarios of high interest. Each of the scenarios investigates different density for mLTE-U and Wi-Fi networks and identifies the combinations of TXOP and muting period that can provide fair coexistence between LTE and Wi-Fi. The fair coexistence is defined in terms of equal throughput ratio achievement for each one of the co-located networks. In the investigated scenarios, all the networks consist of one end-device connected to one base station and they have equal traffic requirements. As it has been revealed from the simulation results, for each scenario multiple configurations can provide the desired fair coexistence. The biggest challenge is to identify and select the optimal parameter values that can guarantee fair coexistence.

This section discusses how these configurations can be automatically identified. This identification can be done taking several parameters into consideration,

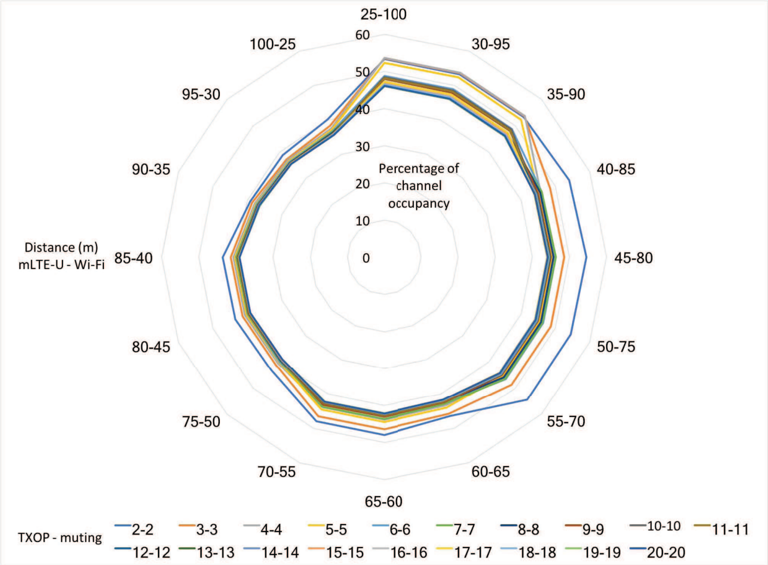

Figure 5.25: Wi-Fi fair channel occupancy for different distances between the UE and the eNB and between the STA and the AP

such as the amount of the co-located networks and the type of traffic that must be served. The traffic that must be served refers to the load of each network and the QoS requirements. The degree that a network can exploit the aforementioned parameters is related to the network architecture. Regarding the network architecture, the co-located networks can be either under the control of a central coordinator or can operate independently.

According to the coordinated approach, the identification of the participating networks and the collection of traffic information can be easy as the coordinator can directly communicate with each network. On the other hand, the existence of a coordinator increases the complexity of the network. Additionally, there always might be other networks in the neighbourhood that do not belong to the coordination scheme. Modifications to the wireless protocols are required in order to render each technology capable of communicating such type of information to the coordinator. The coordinator needs a careful design in order to be able to communicate with different technologies, collect and manage the required information. In such an ideal scenario, the coordinator will be responsible to tune the mLTE-U parameters in order to ensure that each network is able to achieve the required throughput. On the other hand, a non-coordinated approach is more realistic, as every network can be deployed arbitrarily. Such an approach requires lower complexity regarding the overall network architecture as each network operates independently. On the contrary, each network must be responsible to collect the information that is required in order to decide the appropriate configuration that enables fair coexistence with the co-located networks. Wireless technology recognition techniques [7] [30] are required to identify the amount and type of the wireless technologies that are in the proximity of each other. Based on this information, each mLTE-U network can decide the combinations of TXOP and the muting period that can offer the proportional fair throughput.

The discovery of the TXOP and muting period configurations that offer fair coexistence requires careful design. As a first approach, a heuristic technique can be used. According to such a technique, the eNB can try different configurations attempting to find the ones that offer a performance (e.g. throughput) that approaches its target. When a combination of TXOP and muting period is found, the eNB can evaluate other configurations by using neighbouring values for both TXOP and muting period. As it has been observed by the simulation result, neighbouring configuration values are more possible to offer fair coexistence. Hence, for instance if a TXOP duration of 4 ms followed by a muting period of 8 ms is a possible configuration, then a next possible combination could be a TXOP of 5 ms followed by a muting period of 8 ms. As in every learning technique, this method requires a convergence time to identify the desired configurations. In the beginning, the system can operate in acceptable bounds but as the time passes the considered heuristic algorithm approaches to the optimal configuration values in reasonable time. The complexity is in line with our previous work [31], in which two heuristic algorithms for joint power assignment and resource allocation in femtocells are evaluated and optimized in order to achieve the optimal solution in short time. The design of an algorithm that determines the configurations that can offer fair coexistence in an optimal way will be further examined in our future work.

Based on the identified combinations of TXOP and muting period that offer fair coexistence for a specific topology and according to the traffic requirements that must be satisfied, the network can select the optimal configuration that serves them better. For instance, in case of voice traffic (AC_VO), the network must choose a configuration that offers a short muting period and a long TXOP. On the contrast, a network that must serve best-effort traffic (AC_BE) can choose a configuration with longer muting period and shorter TXOP.

Algorithm 5.1 presents the complete procedure as it is described above and is required by an independent mLTE-U network to select an optimal configuration that enables fair coexistence with the co-located LTE or Wi-Fi networks. The algorithm takes as input the traffic requirements that the mLTE-U network has to serve. Then, periodically it performs a technology recognition in order to identify potential co-located LTE or Wi-Fi networks. Based on the discovered networks, the algorithm determines the possible values (TXOP and muting period) that can provide fair coexistence (e.g. using a heuristic technique). Finally, based on the

Algorithm 5.1: mLTE-U optimal configuration selection

Input : t_r, traffic requirements that need to be served by the network

Output: opt[TXOP,muting], optimal combination of TXOP and muting period that can enable fair coexistence between mLTE-U and Wi-Fi in line with the traffic requirements

Data: n_LTE, number of identified co-located LTE networks. n_Wi-Fi, number of identified co-located Wi-Fi networks. c_l[TXOP,muting], configuration list of TXOP and muting period combinations that can enable fair coexistence between mLTE-U and Wi-Fi.

```
while true do
    [n_LTE, n_Wi-Fi] = technology_recognition ()
    if $n\_LTE \geq 1$ || $n\_Wi\text{-}Fi \geq 1$ then
        c_l[TXOP,muting] = possible_fair_values_identification (n_LTE, n_Wi-Fi)
        opt[TXOP, muting] = fairest_config_for_traffic_requirements (c_l[TXOP,muting], t_r)
    end
end
```

traffic requirements, it selects the optimal parameters that enable fair spectrum sharing. Further study and optimization of the techniques that can identify an optimal mLTE-U configuration based on different topologies and traffic requirements for both LTE and Wi-Fi will be investigated in our future work.

5.10 Conclusions and future work

This article proposes a new coexistence scheme that can enable a fair coexistence of LTE-U and Wi-Fi. As it is discussed, a fair coexistence can give to the participating networks opportunities to achieve equal performance in a technology-agnostic manner. The proposed coexistence scheme named mLTE-U, requires a CCA procedure before each mLTE-U transmission. When the CCA mechanism indicates the channel as idle, then the mLTE-U performs a transmission burst of variable duration followed by a muting period of variable duration. The muting period can give further transmission opportunities to coexisting Wi-Fi networks. The proposed mLTE-U scheme and the provided coexistence with Wi-Fi and other mLTE-U networks is evaluated in different scenarios of high interest. These scenarios include different mLTE-U and Wi-Fi network densities, as well as static and moving end-devices. Furthermore, we discuss the procedure according to which an mLTE-U network can select the parameters that can offer the required fair coexistence in a technology-agnostic manner, based on the number of participating networks and the traffic requirements that must be satisfied. The simulation results show that the proper configuration of mLTE-U according to the number of co-located networks can enable fair and harmonious coexistence in unlicensed spectrum.

In the near future, we will further investigate and analyse techniques towards the optimal selection of the mLTE-U parameters that can enable fair coexistence with co-located wireless technologies.

Acknowledgment

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6

A Q-learning Scheme for Fair Coexistence Between LTE and Wi-Fi in Unlicensed Spectrum

Until now, the impact of traditional LTE on Wi-Fi have been measured (Chapter 3) and several cooperation schemes that can enable fair spectrum sharing between the two technologies have been proposed (Chapter 4). Additionally, an adaptive LTE LBT scheme has been introduced and the offered coexistence performance for different scenarios of high interest has been studied (Chapter 5). This chapter goes one step further by introducing a Q-learning technique in order to automatically and autonomously select the mLTE-U parameters that can enable fair spectrum sharing. The proposed system is analyzed in detail and its performance is evaluated for different scenarios. The performance of the proposed Q-learning scheme is compared with other conventional schemes, showing its superiority over less complex methods. This chapter is a modified version of the original homonymous article, which is published in IEEE Access Journal.

⋆ ⋆ ⋆

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Abstract During the last years, the growth of wireless traffic pushed the wireless community to search for solutions that can assist in a more efficient management of the spectrum. Towards this direction, the operation of LTE in unlicensed spectrum (LTE-U) has been proposed. Targeting a global solution that respects the regional regulations worldwide, 3GPP has published the LTE Licensed Assisted Access (LAA) standard. According to LTE LAA, a Listen Before Talk (LBT) procedure must precede any LTE transmission burst in the unlicensed spectrum. However, the proposed standard may cause coexistence issues between LTE and Wi-Fi, especially in the case that the latter does not use frame aggregation. Towards the provision of a balanced channel access, we have proposed mLTE-U that is an adaptive LTE LBT scheme. According to mLTE-U, LTE uses a variable transmission opportunity (TXOP), followed by a variable muting period. This muting period can be exploited by co-located Wi-Fi networks to gain access to the medium. In this article, the system model of mLTE-U scheme in coexistence with Wi-Fi is studied. Additionally, mLTE-U is enhanced with a Q-learning technique that is used for autonomous selection of the appropriate combinations of TXOP and muting period that can provide fair coexistence between co-located mLTE-U and Wi-Fi networks. Simulation results showcase the performance of the proposed model and reveal the benefit of using Q-learning for self-adaptation of mLTE-U to the changes of the dynamic wireless environment, towards fair coexistence with Wi-Fi. Finally, the Q-learning mechanism is compared with conventional selection schemes showing the superior performance of the proposed model over less complex mechanisms.

6.1 Introduction

Over the last years, the technological growth has led to a tremendous increase of wireless devices such as smartphones, laptops and sensor networks, that exchange information with each other. Additionally, the establishment of Internet of Things (IoT) has further increased the number of the wirelessly interconnected devices. The wireless traffic is expected to increase by a factor of 1000 by 2020 compared to that in 2010 [1]. This information is exchanged between devices using different types of wireless technologies such as LTE, IEEE 802.11 (also known as Wi-Fi), IEEE 802.15.4 and Bluetooth. Recently, technologies that target wide range communications such as LORA and SIGFOX exploit sub-GHz bands. Furthermore, high frequency bands such as mmWave are used for mutli-gigabit speeds (IEEE 802.11ad). It is clear that soon the wireless network capacity will become a bottleneck for serving the increased wireless traffic.

Concurrently, the licensed spectrum used by the mobile operators becomes very scarce. The availability of the licensed spectrum combined with the high cost of a licensed frequency band have pushed the mobile operators to investigate solutions that can assist in meeting the 1000x challenge requirements. Among other solutions like (massive) Multiple-Input Multiple-Output (MIMO) and Carrier Aggregation the LTE operation in the unlicensed spectrum (LTE-U) has attracted significant attention from the wireless community. Hence, several techniques have been proposed aiming to achieve harmonious coexistence between LTE and other well-established technologies in the unlicensed spectrum (e.g. Wi-Fi) [2].

In regions where a Listen Before Talk (LBT) procedure before a transmission is not mandatory, such as in U.S.A. or in China, LTE can transmit in unlicensed spectrum using a ON-OFF duty-cycle technique. The most famous technique of this nature is the Carrier Sense Adaptive Transmission (CSAT) [3], which has been proposed by Qualcomm. The duration of the LTE ON and OFF periods are defined by the evolved NodeB (eNB) according to the observed channel utilization, based on the estimated number of Wi-Fi Access Points (AP) [3].

Towards a coexistence technique that respects the regional regulations in regions where an LBT procedure before a transmission in the unlicensed spectrum is mandatory (such as in Europe and in Japan), 3GPP published the LTE License Assisted Access (LTE LAA) standard as part of the Release 13 [4] and Release 14 [5]. The standard includes the description of an LBT procedure that is also known as Clear Channel Assessment (CCA) that must be performed prior to a transmission in the unlicensed spectrum. Furthermore, the LTE operation solely in the unlicensed spectrum has been proposed by leading wireless stakeholders, towards the decoupling of LTE from the operators. To this end, they formed the MulteFire Alliance [6].

Although the LTE LAA standard defines that a CCA procedure must be performed before a transmission in the unlicensed spectrum, it also defines four channel access priority classes. Each priority class specifies among others the transmission duration in unlicensed channel after it has been estimated as idle. This transmission duration varies from 2 up to 10 ms. On the other hand, when frame aggregation is not enabled or supported by the 802.11 standard, a typical Wi-Fi transmission lasts for few hundreds of μs [7]. Even when frame aggregation is used, a significant percentage of packets requires a short transmission time. In [8], it has been evaluated that 50% of the packets are transmitted within 30 μs, while 80% of the packets are transmitted within 1 ms. This shows that the ratio between LTE and Wi-Fi transmission time occupancy is not balanced. This can lead to unfair coexistence between the two networks in the unlicensed spectrum.

In our previous work [9] and based on this observation, a novel coexistence mechanism named mLTE-U has been proposed and builds on elements of LTE Release 13. mLTE-U is an adaptive LTE-U transmission scheme, according to which LTE can transmit Downlink (DL) traffic in the unlicensed spectrum after the channel has been assessed as idle, using a variable transmission opportunity (TXOP) period followed by a variable muting period. This muting period can give channel access opportunities to other potentially co-located networks such as Wi-Fi. From the different possible pairs of TXOPs and muting periods, the selection of the appropriate combination has to be done in a way that the co-located networks share the medium in a fair way. The mLTE-U scheme has been evaluated using an event-based simulation platform.

This article further extends this work by studying the system model of the mLTE-U mechanism in coexistence with Wi-Fi and by introducing reinforcement learning and specifically Q-learning, as it is able to provide automatic and autonomous selection of the appropriate TXOP and muting period combinations that can enable fair coexistence. Q-learning is a technique that converges to optimal policies. Another advantage of Q-learning is that it does not require a prior environment model [10]. This is suitable for dynamic and arbitrary environments such as wireless environments. The main contribution of this work is summarized as follows:

- Description and analysis of the system model for the proposed mLTE-U scheme when it coexists with Wi-Fi or other mLTE-U networks
- Discussion about fair coexistence in unlicensed spectrum, definition of fairness as equal sharing of spectrum in a technology-agnostic way and problem formulation of mLTE-U TXOP and muting period selection towards fair spectrum sharing
- Use of Q-learning mechanism for optimal and autonomous selection of mLTE-U TXOP and muting period towards fair coexistence
- Performance evaluation of the proposed mLTE-U coexistence scheme with and without using Q-learning mechanism through simulations
- Comparison of Q-learning with conventional selection mechanisms such as random selection and round-robin

The remainder of the article is organized as follows. Section 6.2 gives an overview of the current literature on the coexistence of LTE-U and Wi-Fi and the exploitation of Q-learning towards the selection and adjustment of coexistence parameters. In Section 6.3, we discuss the problem that arises when LTE LAA coexists with traditional Wi-Fi networks that do not use frame aggregation and we give a summarized description of the mLTE-U scheme. Next, in Section 6.4, we analyze the system model of the mLTE-U scheme, when it coexists with Wi-Fi. Section 6.5 discusses the topic of fair coexistence in unlicensed spectrum and the approach followed in this article. Section 6.6 analyses the integration and usage of a Q-learning mechanism in mLTE-U towards autonomous and optimal selection of the mLTE-U parameters. In Section 6.7, we describe the simulation environment that has been used, while Section 6.8 evaluates the performance of the proposed technique and compares it with conventional selection schemes. Finally, Section 6.9 concludes the paper and discusses plans for future work.

6.2 Related work

6.2.1 Coexistence between LTE-U and Wi-Fi

From the moment LTE-U was firstly introduced, there were serious concerns from the wireless community about unfair coexistence of LTE with other well-established technologies in the unlicensed spectrum, such as Wi-Fi. These concerns were based on the fact that LTE is designed to be a scheduled technology that does not use a CCA mechanism to sense the medium before a transmission. Hence, it would transmit arbitrarily forcing the other networks to continuously backoff. In our previous work [11], we studied the impact of a traditional LTE operating in unlicensed spectrum on Wi-Fi using Off-The-Shelf (OTS) hardware equipment at the LTE testbed of IMEC [12]. Three different levels of LTE signal power have been examined that represent different possible levels of LTE impact on Wi-Fi. According to the results, the Wi-Fi performance can be significantly affected by LTE. Several other studies [13] [14] [15] evaluate the impact of LTE on Wi-Fi through experiments, mathematical models and simulations, all coming to the same conclusion, namely that coexistence mechanisms are required to render LTE fair towards other co-located technologies, like Wi-Fi.

Lately, several coexistence mechanisms have been proposed, targeting to improve the coexistence between LTE and Wi-Fi. Similar to the CSAT mechanism that is described in Section 6.1, the authors in [16] propose a coexistence scheme that exploits periodically blank LTE subframes during an LTE frame in order to give transmission opportunities to Wi-Fi. The scheme is evaluated via simulations and it is concluded that the number and the order of the blank subframes have an impact on the provided coexistence.

In our previous work [17], the concept of LTE-U has been extensively studied. To this end, a detailed analysis of the current state-of-the-art regarding LTE-U and Wi-Fi is given. Additionally, a classification of techniques that can be applied between co-located LTE and Wi-Fi networks is presented. This classification combined with the study of the literature revealed the lack of cooperation schemes among co-located networks that can lead to more optimal use of the available spectrum. In order to fill this gap, we proposed several concepts of cooperation techniques that can enhance the spectral efficiency between coexisting LTE and Wi-Fi networks. The proposed techniques are compared between each other in terms of complexity and performance.

As it has been discussed in Section 6.1, 3GPP announced the LTE LAA as part of Release 13, towards a global coexistence technique that respects the regional regulations worldwide. The strong point of this technique is that it includes the description of a CCA procedure that must be performed before a transmission in the unlicensed spectrum to verify the availability of the channel [4]. The concept of the adoption of a CCA procedure by LTE has been proposed in several works. The authors in [18] propose an LBT scheme for LTE LAA that enhances the coexistence with Wi-Fi and increases the overall system performance. The scheme comprises of two parts named on-off adaptation for channel occupancy time and short-long adaptation for idle time. According to the first mechanism, the channel occupancy time of LTE can be adapted based on the load of the network, while according to the second one the idle period can be adapted based on the Contention Window (CW) duration of Wi-Fi.

The authors in [19], propose a MAC layer for LTE-U that uses LBT and channel reservation packets. The LBT can be either synchronous or asynchronous. Furthermore, in order to cope with potential collisions, they propose improvements to the LTE link adaptation algorithm. The simulation results show that the performance of co-located Wi-Fi can be improved by the proposed MAC design. The LTE-U cell edge performance can be also improved by the channel reservation mechanism.

In [20], the authors study the coexistence between LTE LAA and Wi-Fi using LBT Category 4 (Cat 4) channel access scheme. The behavior of the eNB is modeled as a Markov chain. The authors adopt the obtained throughput as performance indicator. The proposed LBT scheme uses an adaptive CW size for LTE LAA. The results show that the proposed scheme can achieve higher performance compared to the fixed CW size scheme.

The authors in [21] propose an LBT mechanism for LTE LAA that aims to share the medium in a fair way and concurrently to increase of the overall system performance. This work analyses mathematically the proposed LBT scheme and additionally, it is validated via simulations. The results show that the performance of Wi-Fi can be increased by proper selection of LAA channel occupancy and the backoff counter.

A detailed survey of the coexistence between LTE and Wi-Fi on 5 GHz with corresponding deployment scenarios is given in [22]. The authors give a detailed description of the coexistence-related features of LTE and Wi-Fi, the challenges, the differences in performance between the two different technologies and co-channel interference. They discuss in detail the proposed coexistence techniques between LTE and Wi-Fi that have been proposed in the literature. Moreover, the survey analyses the concept of scenario-oriented coexistence. According to this concept, coexistence-related problems can be solved according to different deployment scenarios.

6.2.2 Coexistence enhancement with Q-learning

Q-learning has been used in various works to enhance the coexistence mechanisms and render them capable to learn individually the best possible strategies in order to achieve a target. In [23], the authors propose a Q-learning-based dynamic duty cycle selection mechanism for the configuration of LTE transmission gaps. LTE LAA and Wi-Fi performance using a fixed transmission gap is evaluated and is used as reference scenario. Then, the proposed Q-Learning mechanism is compared with the reference scenario. Simulation results show that the proposed scheme enhances the overall capacity performance.

The authors in [24] propose a fair DL traffic management scheme. This scheme targets to adapt the minimum CW values and assign feasible weights to the LAA eNBs with different traffic loads. This way, they aim to achieve fair spectrum sharing with coexisting Wi-Fi networks and service differentiation for DL LTE LAA traffic. Simulation results show that the proposed scheme can offer fair coexistence with Wi-Fi networks and can provide proportional fairness to LAA eNBs with different traffic requirements.

In [25], a docitive Q-learning scheme for joint resource allocation and power control is proposed. In this scheme, the femto base stations learn the optimal strategies by exploiting Q-learning and share their knowledge with their neighbors. The target of the learning scheme is the maximization of the femtocell capacity, while maintaining the quality of service requirement of the macro-users. The proposed scheme is compared with the independent learning in terms of convergence, min-max capacity and the impact on the femtocell density.

A channel selection mechanism using Q-learning for LTE-U is proposed in [26]. This mechanism decides the most appropriate channel in unlicensed spectrum for a small cell base station. Different indoor scenarios with small cells belonging to two different operators have been studied. The results show that the proposed approach is capable to achieve a performance between 96% and 99% of the optimum throughput.

In [27], a Q-learning mechanism for advanced learning of the activity within an unlicensed band is proposed. This mechanism results in enhanced coexistence between LTE LAA and Wi-Fi. Furthermore, the coexistence is further enhanced through a double Q-learning method. This method takes into account both transmit power control of LTE and discontinuous transmission. Simulation results show that the proposed methods are capable to improve both LTE and Wi-Fi performance.

6.2.3 Enhancement of mLTE-U scheme with Q-learning

Although 3GPP published the LTE LAA standard that describes a CCA procedure that must be performed before a DL transmission, the ratio between LTE LAA and

Wi-Fi TXOP is not balanced, especially when Wi-Fi does not use or support frame aggregation. In order to balance the TXOP of LTE and Wi-Fi, in our previous work [9], we proposed an adaptive LTE LBT scheme named mLTE-U. Similar to LTE LAA, this scheme uses an anchor channel in licensed band together with a secondary channel in unlicensed spectrum, which can be exploited by the eNB to transmit DL traffic. mLTE-U requires a CCA procedure before a DL transmission in the unlicensed spectrum and uses adaptable LTE TXOP followed by an adaptable muting period. The muting period can be exploited by other co-located technologies, such as Wi-Fi, to gain access to the medium. The provided coexistence performance depends on the selection of TXOP and muting period duration. This article further extends our previous work by introducing a Q-learning technique for autonomous selection of the optimal TXOP and muting period by an mLTE-U eNB that can enable fair coexistence between mLTE-U and Wi-Fi. Additionally, this article provides a system model analysis of the mLTE-U scheme in coexistence with Wi-Fi, in comparison to [9], where the mLTE-U scheme has been implemented and evaluated using the NS3 simulation platform.

6.3 Problem definition and the proposed solution

Recently, 3GPP published the LTE LAA standard in order to enable the LTE operation in unlicensed spectrum as part of LTE Release 13. In order to satisfy the regulations in regions where an LBT procedure is mandatory, such as Europe and Japan, LTE LAA defines a CCA procedure that must be performed before a DL LTE transmission in the unlicensed spectrum. Before a transmission, an eNB has to evaluate the availability of the channel. If the channel is busy, then it must defer its transmission and perform an exponential backoff. When the channel is idle, then the eNB starts a transmission burst for a duration that ranges from 2 ms up to 10 ms. The transmission duration is defined by four different channel access priority classes. Table 6.1 presents the different priority classes as they are defined by the 3GPP LTE LAA standard. According to the standard, the priority classes 3 and 4 use a $\mathrm{T}_{\mathrm{m\,cot,p}}$ that is equal to 10 ms if the absence of any other co-located technology sharing the same channel can be guaranteed on a long term basis. Otherwise, the LTE transmission duration in unlicensed spectrum is limited to 8 ms. In this table, m_p is the number of slots in a defer period, while CW_{min} and CW_{max} are the respective minimum and maximum values of the CW size.

On the contrary, in traditional Wi-Fi networks, the AP or the station (STA) transmits only one packet after the medium is estimated as idle, when frame aggregation is not supported or is not enabled. Such transmission typically lasts for a few hundreds of μs. In various widely used Wi-Fi standards such as 802.11a/g frame aggregation is not supported, but even if it is available (e.g. 802.11n/ac [28]), in several cases it is not used depending on the traffic type constraints such as low

Table 6.1: Channel access priority class configuration of LTE LAA

Channel access priority class (p)	m_p	$CW_{min,p}$	$CW_{max,p}$	$T_{m\,cot,p}$	Allowed CW_p sizes
1	1	3	7	2 ms	3,7
2	1	7	15	3 ms	7,15
3	3	15	63	8 or 10 ms	15,31,63
4	7	15	1023	8 or 10 ms	15,31,63,127,255,511,1023

latency [29]. Additionally, 802.11e uses Enhanced Distributed Channel Access (EDCA) that defines four Access Categories (AC) [7]. Two of these AC, named Background (AC_BK) and Best Effort (AC_BE), define TXOPs of only a single frame. The other two, named Video (AC_VI) and Voice (AC_VO), define TXOPs of $3.008ms$ and $1.504ms$ duration respectively. However, these TXOPs are not balanced compared to the TXOPs defined for LTE LAA that can go up to $10ms$ and although they have defined by the standard, practical implementations rarely use them.

It is clear that the ratio between the transmission duration of LTE and Wi-Fi in the unlicensed spectrum is not balanced as the TXOP duration of LTE LAA is significantly longer compared to the single packet transmission of Wi-Fi. In order to deal with this concern, in our previous work [9], we proposed the mLTE-U coexistence mechanism. mLTE-U is a novel and adaptable technique that enables fair coexistence between LTE and Wi-Fi. Before a transmission in the unlicensed band, mLTE-U must perform an LBT Cat 4 procedure. If the medium is estimated as idle, LTE can transmit DL traffic for a variable TXOP duration, followed by a variable muting period. Without loose of generality, the TXOP is selected in a range of 2 ms up to 20 ms and the muting period is selected in a range of 0 ms up to 20 ms. Fig. 6.1 shows the mLTE-U scheme.

In [9], the proposed scheme has been evaluated under different coexistence scenarios (low to high LTE and Wi-Fi density), investigating the different combination of TXOP and muting period. This article goes a step further by analytically studying the system model of mLTE-U in coexistence with Wi-Fi and by employing a reinforcement learning technique, more specifically a Q-learning technique, so that an eNB can automatically and autonomously select the optimal configuration parameters (TXOP and muting period) that can lead to fair coexistence with other co-located networks.

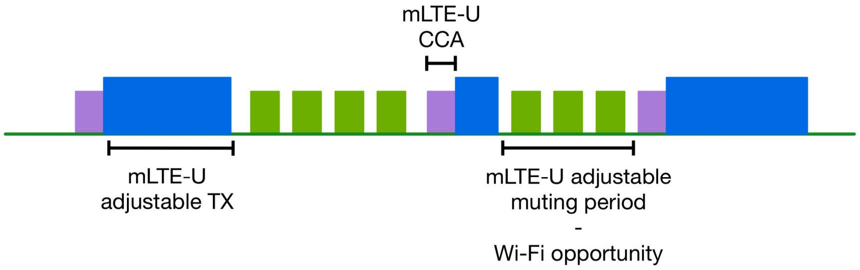

Figure 6.1: The design of the mLTE-U scheme

6.4 System model

This section aims to analyze the system model of the proposed mLTE-U scheme, when it coexists with Wi-Fi. All the participating networks operate autonomously and cannot exchange messages with each other. In this work and similar to LTE Release 13, the eNB is able to transmit in the unlicensed spectrum, while the Uplink (UL) traffic is transmitted via the primary licensed band. We consider as active any mLTE-U eNB, Wi-Fi AP and Wi-Fi STA node that has traffic to transmit in unlicensed spectrum. All the active nodes use the same LBT algorithm with random backoff and variable size of CW (similar to LBT Cat 4). For instance, we consider a scenario where one mLTE-U network consisting of one eNB and one UE coexists with one Wi-Fi network consisting of one AP and one STA. If the eNB, the AP and the STA have data to transmit, then all these three nodes are indicated as active. On the other hand, if only the eNB and the AP have data to transmit, then only these two nodes are indicated as active. It is assumed that all the co-located networks transmit in a single unlicensed channel. For the sake of simplicity, we assume that all the networks are in the proximity of each other. This means that every transmission can be determined by the Energy Detection (ED) mechanism of CCA for both mLTE-U and Wi-Fi networks. ED is a function used by CCA to determine the state of the channel, when the received signal cannot be decoded. The CCA mechanism of 802.11 uses also a second function, named Carrier Sense (CS). CS is used when the receiver is able to detect and decode a received Wi-Fi preamble [7].

Both mLTE-U and Wi-Fi use a Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) mechanism to compete for the channel access. Before a transmission, every network has to perform CCA in order to sense the channel and discover if it is idle or busy. Before a new transmission or after a successful transmission, a node has to postpone its transmission for Distributed Coordination Function (DCF) Inter-Frame Space (DIFS) plus a random backoff time. The backoff time corresponds to the number of idle timeslots (ts) that a node has to sense before a transmission. The number of the ts is indicated by the backoff counter, which is randomly selected within the range of the CW. If a transmission is not successful and an acknowledgment (ACK) is not received, the CW increases exponentially. For both mLTE and Wi-Fi the CW ranges from $\mathrm{CW}_{\mathrm{min}}$ to $\mathrm{CW}_{\mathrm{max}}$.

We denote the number of the active mLTE-U eNBs as L and the number of active Wi-Fi APs and active Wi-Fi STAs as *A* and *S* respectively. The total number of the active Wi-Fi nodes is denoted as *W*, where $W = A + S$. The probability that a node tries to transmit at any moment is independent of the previous transmissions. Furthermore, the transmission probability is related to the size of the CW. By assuming that the probability of a transmission to be involved in a collision is very small, the transmission probability of the i-th mLTE-U eNB p_i and the transmission probability of the j-th Wi-Fi node r_j both depend on the $\mathrm{CW}_{\mathrm{min}}$ and respectively are equal to:

$$p_{\mathrm{i}} = \frac{1}{CW_{\mathrm{min,i}} + 1}, \quad i = 1, ..., L \tag{6.1}$$

and

$$r_{\mathrm{j}} = \frac{1}{CW_{\mathrm{min,j}} + 1}, \quad j = 1, ..., W \tag{6.2}$$

As in the current model an mLTE-U eNB and a Wi-Fi node use the same $\mathrm{CW}_{\mathrm{min}}$ value, they have equal probabilities to access the medium.

According to the CCA mechanism that is used by both networks, the time frame can be divided into four different slots:

1. Collision slot $\mathrm{T}_{\mathrm{col}}$, meaning that more than one of the co-located nodes (eNBs, APs or STAs) attempt to transmit simultaneously
2. Empty slot $\mathrm{T}_{\mathrm{empty}}$, meaning that none of the nodes attempts to transmit
3. Successful mLTE-U transmission slot $\mathrm{T}_{\mathrm{mLTE\text{-}U}}$, meaning that only one eNB transmits, while the rest eNBs and all the Wi-Fi nodes remain silent
4. Successful Wi-Fi transmission slot $\mathrm{T}_{\mathrm{Wi\text{-}Fi}}$, meaning that only one Wi-Fi node transmits, while the rest Wi-Fi nodes and all the eNBs remain silent

Fig. 6.2 illustrates the system model of mLTE-U when it coexists with Wi-Fi.

The transmissions of each co-located network are independent and identically distributed (i.i.d.). Hence, the probability that the i-th mLTE-U eNB transmits successfully during a slot is:

$$p_{succ,i}^{mLTE-U} = p_{\mathrm{i}} \times \prod_{l \neq i}^{L} (1 - p_{\mathrm{l}}) \times \prod_{j=1}^{W} (1 - r_{\mathrm{j}}) \tag{6.3}$$

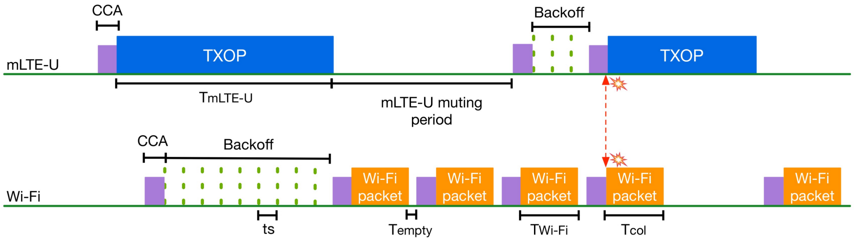

Figure 6.2: The system model of mLTE-U in coexistence with Wi-Fi

Similarly, the probability that the j-th Wi-Fi node transmits successfully during a slot is:

$$p_{succ,j}^{Wi-Fi} = r_{\mathrm{j}} \times \prod_{w \neq j}^{W} (1 - r_{\mathrm{w}}) \times \prod_{i=1}^{L} (1 - p_{\mathrm{i}}) \tag{6.4}$$

The probability that a slot is empty is expressed as:

$$p_{\text{empty}} = \prod_{i=1}^{L} (1 - p_{\mathrm{i}}) \times \prod_{j=1}^{W} (1 - r_{\mathrm{j}}) \tag{6.5}$$

while the probability that a collision occurs in a slot is given by:

$$p_{\text{col}} = 1 - p_{\text{empty}} - \sum_{i=1}^{L} (p_{succ,i}^{mLTE-U}) - \sum_{j=1}^{W} (p_{succ,j}^{Wi-Fi}) \tag{6.6}$$

The total duration of the slots is expressed as:

$$T_{\text{total}} = Tot_{\text{empty}} + Tot_{\text{col}} + Tot_{\text{Wi-Fi}} + Tot_{\text{mLTE-U}} \tag{6.7}$$

where Tot_{empty} and Tot_{col} denote the total duration of the empty and the collision slots respectively, $Tot_{\text{Wi-Fi}}$ denotes the total duration of the successful Wi-Fi transmissions and $Tot_{\text{mLTE-U}}$ represents the total duration of the successful mLTE-U transmissions in unlicensed spectrum.

Furthermore, the total combined throughput of Wi-Fi can be calculated by:

$$Thr_{\text{Wi-Fi}} = \sum_{j=1}^{W} \left(\frac{D_{Thr,j}^{Wi-Fi}}{T_{\text{total}}}\right) \tag{6.8}$$

where $D_{Thr,j}^{Wi-Fi}$ is the transmitted payload of Wi-Fi node j. Similarly, the total combined throughput of mLTE-U in the unlicensed band is expressed as:

$$Thr_{\text{mLTE-U}} = \sum_{i=1}^{L} \left(\frac{D_{Thr,i}^{mLTE-U}}{T_{\text{total}}} \right) \tag{6.9}$$

where $D_{Thr,i}^{mLTE-U}$ is the transmitted payload of the i-th mLTE-U eNB.

6.4.1 Reservation signal

An mLTE-U eNB must perform a CCA procedure before a transmission to estimate if the channel is idle or not. Hence, the medium can be sensed as idle at any time. However, LTE is a scheduled technology on a sub-frame level, meaning that every 1 ms the eNB scheduler assigns the wireless resources to the active UE. This means that every data transmission starts at the beginning of a subframe. To deal with this issue and similar to our previous work in [9], a reservation signal is used for mLTE-U in order to reserve the channel after it is sensed as idle and before the beginning of the next subframe. Fig. 6.3 illustrates the use of the reservation signal.

The reservation signal is modeled by a uniformly distributed random variable in the interval [0,1]. A value close to zero corresponds to a short duration of reservation signal. This means that the channel is sensed as idle towards the ending of a subframe. A value close to one means that the channel is sensed as idle in the beginning of a subframe. Thus, the reservation signal is transmitted for the rest of the subframe duration. The duration of the reservation signal is deducted from the TXOP duration of the mLTE-U scheme. For this reason, the minimum examined TXOP duration is 2 ms.

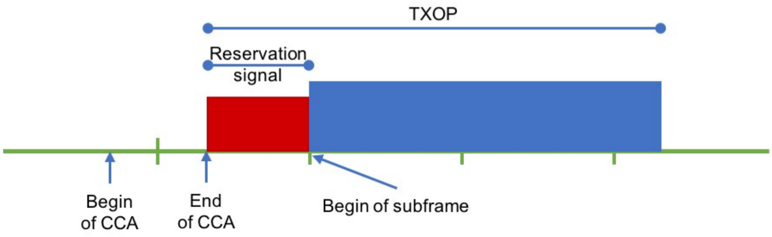

Figure 6.3: The reservation signal of the mLTE-U scheme

6.5 Fair coexistence

This section discusses the way that the two different parameters of mLTE-U scheme, named TXOP and muting period, can be selected in order to ensure fair coexistence between co-located mLTE-U and Wi-Fi networks. A fair coexistence scheme should be able to provide to all the active nodes in the unlicensed spectrum equal opportunities to the wireless resources. This must be done in a technology-agnostic way, as all the nodes must be treated equally. According to this approach, all the active mLTE-U eNBs, Wi-Fi APs and Wi-Fi STAs should be able to gain equal spectrum access.

In an ideal world in which the different wireless technologies can communicate with each other, exchange their spectral requirements and operate altruistically, the distribution of the wireless resources could be done in a fair and harmonious way. However, in the real wireless world, several diverse wireless technologies that have been designed, each having different target groups, different principles and different requirements are forced to coexist with each other. Additionally, the channel access mechanism of the different technologies vary significantly between each other. In [9], we saw that the obtained throughput, as well as the percentage of channel occupancy are good indicators for measuring the fairness that a co-existence technique can provide. According to this approach, the parameters of mLTE-U must be selected in a way that every co-located network can achieve an equal ratio of throughput, compared to the maximum throughput that it can achieve when it operates in standalone mode, meaning that it operates without any other co-located network.

This assumption requires that every node is able to identify potential co-located networks and approximate the number of transmitting devices. This can be achieved using a wireless technology recognition technique. Recently, the technology recognition problem has attracted the attention of the wireless community. As result, several techniques (e.g. [8] and [30]) have been proposed and can be used by an mLTE-U network to identify the amount and the type of co-located wireless technologies. Based on this information, an mLTE-U network can select the TXOP and muting period so that it can offer the desired proportional fair throughput. Further discussion on the nature of these techniques is not in the scope of this article and it is assumed that such a technology recognition technique is available to an mLTE-U eNB.

In our system, the target throughput of an mLTE-U network can be expressed as:

$$Thr_{target,i}^{mLTE-U} = \frac{Thr_{standalone,i}^{mLTE-U}}{L+W} \tag{6.10}$$

where $Thr_{standalone,i}^{mLTE-U}$ is the throughput that the mLTE-U network i can achieve in standalone operation using the maximum TXOP configuration (20 ms) and a muting period that is equal to zero. A muting period that is equal to zero ensures that the eNB can start competing for the medium immediately after finishing a transmission of TXOP duration. Moreover, the highest TXOP ensures that the eNB can transmit for a longer period without interruption. The configuration of

TXOP has an impact on the obtained throughput. For a lower TXOP, the eNB has to perform a CCA procedure more frequently compared to a higher TXOP. This forces the eNB to spend more time evaluating the channel compared to the case in which it uses a high TXOP.

Considering the system that is described in Section 6.4, the configuration of TXOP and muting period for an mLTE-U eNB must be selected according to the following optimization problem:

$$\begin{aligned}
(TXOP_i^*, muting_i^*) = arg \max_{TXOP,muting} &(\mid (\mid Thr_{target,i}^{mLTE-U} \\
&- Thr_i^{mLTE-U} \mid) - Thr_{target,i}^{mLTE-U} \mid) \\
\text{s.t.}\quad & C1: \ 0 \le p_{\mathrm{i}} \le 1, \qquad i = 1, ..., L \\
& C2: \ 0 \le r_{\mathrm{j}} \le 1, \qquad j = 1, ..., W \\
& C3: \mid Thr_{target,i}^{mLTE-U} - Thr_i^{mLTE-U} \mid \le \zeta, \ \ i = 1, ..., L \\
& C4: \ TXOP \in [TXOP_{min}, TXOP_{max}] \\
& C5: \ muting \in [muting_{min}, muting_{max}]
\end{aligned} \tag{6.11}$$

This problem guarantees that the optimal TXOP and muting period values will be selected so that the obtained mLTE-U throughput will be maintained close to the target value, offering this way fair coexistence with other co-located mLTE-U or Wi-Fi networks. The first constraint (C1) refers to the transmission probability of an mLTE-U eNB, while the second constraint (C2) refers to the transmission probability of a Wi-Fi node. The third constraint (C3) indicates that the absolute difference between the target throughput of eNB *i* and the throughput that eNB *i* achieves after the TXOP and muting period adjustment remains within a tolerance range that is defined by ζ. This constraint ensures that the mLTE-U throughput will remain in an acceptable range close to the target throughput, giving transmission opportunities to other co-located networks. The fourth (C4) and the fifth (C5) constraints ensure that the selected values of TXOP and muting period will be within an acceptable range.

6.6 Proposed Q-learning for fair coexistence between mLTE-U and Wi-Fi

This section discusses how Q-learning can be used in the described model so that an eNB of an mLTE-U network can learn from the environment and autonomously select the appropriate TXOP and muting period combination that can enable fair coexistence with other co-located mLTE-U or Wi-Fi networks.

Q-learning is a type of Reinforcement Learning (RL) in the area of machine learning. According to Q-learning, an agent in a state s selects and performs an action a. After the action a, it observes the environment and receives a reward r for this specific action a. A discount factor γ models the percentage that future rewards are taken into account compared to immediate rewards. Hence, the scope of Q-learning is to find the optimal policy π^* for selecting an action in a given state that maximizes the value of the total reward. In order to learn this policy an agent has to estimate a value-function through experience. This function is called Q-function $Q^\pi(s,a)$ [31]. The Q-function expresses the expected accumulated discounted future reward r that is obtained at time t by selecting an action a in a state s and by following thereafter a policy π. This can be expressed as follows:

$$Q^\pi(s,a) = E(\sum_{t=1}^{\infty} \gamma^{t-1} r_t | s_1 = s, a_1 = a, \pi) \tag{6.12}$$

Q-learning does not require a prior environment model and it can be applied to any given Markov Decision Process (MDP) model. The interaction of an agent with the dynamic stochastic environment is represented by an experience tuple (s_t, a_t, s_{t+1}, r_t), where s_t is the state of an agent at time t and a_t is the action that the agent chooses at time t from the set of the available actions. Then, the agent moves to a new state s_{t+1} at time $t+1$, in which a reward r_t associated with the transition from the state s_t to the state s_{t+1} is determined. The Q-learning process can be represented by the following update equation:

$$Q_{\text{t+1}}(s_t, a_t) \leftarrow Q_{\text{t}}(s_t, a_t) + \eta[r_t + \gamma Q' - Q_{\text{t}}(s_t, a_t)] \tag{6.13}$$

where η is the learning rate and γ is the discount factor. The learning rate can be set between 0 and 1. It determines the percentage that the newly learned information will overwrite the older knowledge. By setting the learning rate to 0 the Q-values are never updated and as result nothing is learned. By setting it to a high value such as 0.9 means that the agent learns at a faster rate. The discount factor γ takes values in the range [0,1]. When it is set to a value closer to one, the agent will consider future rewards with greater weight. The value of Q' indicates the maximum reward that can be attained in a state following the current one. In other words, it expresses the reward for performing the optimal action from the current state and is denoted as follows:

$$Q' = \max_{a \in A} Q_{\text{t}}(s_{t+1}, a_t) \tag{6.14}$$

where A is the set of all the possible actions ($A = \{a_1, a_2, ..., a_i\}$) of the i-th agent.

6.6.1 Definition of Q-learning elements

In the investigating learning scenario, an eNB of an mLTE-U network must learn to be configured with the appropriate TXOP and muting period values that offer fair coexistence with other mLTE-U or Wi-Fi networks using Q-learning. To this end, the agents, states, actions and rewards for the Q-learning algorithm are defined as follows:

6.6.1.1 Agent

In the investigated multi-agent scenario, every *i-th* eNB of an mLTE-U network is an agent, $\forall i = 1, ..., L$.

6.6.1.2 State

For every agent the state is selected by the interaction with the environment. The state s_t^i for an agent i at the time instance t is represented as $s_t^i = \{TXOP^i, muting^i\}$, where $TXOP^i \in [2, 20]$ and $muting^i \in [0, 20]$ is the TXOP and the muting period for the agent *i* respectively.

6.6.1.3 Action

The action of the agent *i* is to select the TXOP and muting period that can offer fair coexistence with other co-located wireless technologies.

6.6.1.4 Reward

The reward for an action *a* of the agent *i* is given by the following function:

$$r_i^{mLTE-U} = \begin{cases} \beta \times (\mid (\mid Thr_{target,i}^{mLTE-U} - Thr_i^{mLTE-U} \mid) \\ \qquad\qquad\qquad\qquad -Thr_{target,i}^{mLTE-U} \mid) \\ \text{for perf\_dif} < \zeta \\ \\ -100 \\ \text{for perf\_dif} \geq \zeta \end{cases} \tag{6.15}$$

where β determines the fraction of the positive reward, perf_dif $= \mid Thr_{target,i}^{mLTE-U} - Thr_i^{mLTE-U} \mid$ is the absolute value of the difference in performance between the target throughput of i-th eNB and the throughput that the i-th eNB achieves after action *a* has been performed. Similar to the third constraint in (6.11), ζ defines a tolerance range for the achieved throughput in a state *s*. Hence, if after an action the obtained throughput is close to the target throughput ($Thr_{target,i}^{mLTE-U}$) meaning that their absolute difference is within the tolerance range, then the agent receives a reward that is proportional to the deviation of the obtained throughput from the target throughput. Otherwise, the agent receives a negative reward.

6.6.2 Exploration strategy

The scope of Q-learning is to find an optimal strategy in the selection of an action a from a state s. Hence, a balance between exploration and exploitation must be found. When an agent exploits, it selects the currently expected optimal action (Q'). On the other hand, when it explores, it selects randomly an action in the hope that it will offer a higher cumulative reward in the future. Hence, by exploring, an agent investigates new actions, while by exploiting it selects the optimal action from the already investigated actions. In this article, the ϵ-greedy policy is used as exploration strategy. ϵ-greedy uses $0 \leq \epsilon \leq 1$ in order to decide if the agent will explore or exploit in every step. The agent chooses a random action (explore) with probability ϵ and the action with the highest Q-value from the current state (exploit) with probability $1 - \epsilon$. When ϵ is configured with a high value, more exploration actions are selected by the agent. This is useful for an agent to learn the environment and the optimal policy.

In this article, an adjustable policy for the value of ϵ is used. Initially or every time that a change to the wireless environment is sensed by the technology recognition technique, ϵ will be set to a high value (e.g. 1) in order to quickly explore different states. After a number of iterations i_ϵ the value of ϵ will be reduced by a p_ϵ value (e.g. 0.05), until a minimum value of ϵ (m_ϵ) is reached (e.g. 0.05) or until the Q-learning converges to the optimal solution.

Algorithm 6.1 presents the proposed Q-learning procedure as it is described above and is required by an independent mLTE-U network to select an optimal configuration that enables fair coexistence with the co-located LTE or Wi-Fi networks.

Regarding the computational complexity of the Q-learning mechanism and similarly to other learning methods, a learning phase is required. During this phase, an agent discovers the environment by investigating different possible actions in every possible state. However, once the environment is learned, the best action can be performed in any given state resulting in the optimal solution. In case that the technology recognition technique is not completely accurate, then the proposed scheme can still achieve performance close to the optimal one.

6.7 Simulation environment

In order to evaluate the proposed mLTE-U scheme and the Q-learning algorithm for optimal and autonomous selection of the mLTE-U parameters, simulations have been performed using MATLAB.

For an mLTE-U network only the throughput in the unlicensed spectrum is taken into consideration. Furthermore, it is assumed that only LTE DL data traffic

Algorithm 6.1: Q-learning for mLTE-U optimal configuration selection

```
Initialization:
$TXOP_{min}$, minimum TXOP value and $TXOP_{max}$, maximum TXOP value
$muting_{min}$, minimum muting value and $muting_{max}$, maximum muting value
$t\_r$, technology recognition result
$\epsilon$, set the $\epsilon$-greedy to a high value (e.g. 1)
$i\_\epsilon$, set the number of the iterations before reduce $\epsilon$
$p\_\epsilon$, set the rate in which $\epsilon$ will be reduced
$m\_\epsilon$, set the minimum value of $\epsilon$
$\zeta$, set the throughput tolerance
$\beta$, set the fraction of the positive rewards
$\eta$, set the learning rate
$\gamma$, set the discount factor
for every i-th mLTE-U eNB, where i = 1, ..., L do
    Set $iteration = 0$, $Q_{i,0}(s, a) = 0$
    Randomly choose a starting state $s_{i,0} = TXOP_{i,0}, muting_{i,0}$ and evaluate it
end
Learning procedure:
while (t_r has not changed) OR (convergence is not achieved) do
    if (a number of iterations $i\_\epsilon$ has been reached) & ($\epsilon > m\_\epsilon$) then
        $\epsilon = \epsilon - p\_\epsilon$
    end
    Randomly choose $prob\_e \in [0, 1]$
    if $prob\_e < \epsilon$ then
        [exploration procedure]
        Select the next action $a_{i,t}$ randomly
    else
        [exploitation procedure]
        Select the next action $a_{i,t}$ based on the max(Q-value): $maxQ_{i,t}(s_{i,t}, a_{i,t})$
    end
    Execute $a_{i,t}$
    Receive an immediate throughput $Thr_{i,t}^{mLTE-U}$
    if ($| Thr_{target,i}^{mLTE-U} - Thr_{i,t}^{mLTE-U} | < \zeta$) then
        $r_{i,t}^{mLTE-U} = \beta \times (| (| Thr_{target,i}^{mLTE-U} - Thr_{i,t}^{mLTE-U} |) - Thr_{target,i}^{mLTE-U} |)$
    else
        $r_{i,t}^{mLTE-U} = -100$
    end
    Update the Q-table (according to 6.13) as follows:
    $Q_{\text{i,t+1}}(s_{i,t}, a_{i,t}) \leftarrow Q_{\text{i,t}}(s_{i,t}, a_{i,t}) + \eta[r_{i,t}^{mLTE-U} + \gamma \max_{a_{i,t} \in A} Q_{\text{i,t}}(s_{i,t+1}, a_{i,t}) - Q_{\text{i,t}}(s_{i,t}, a_{i,t})]$
    Next state: $s_{i,t+1}$
end
```

```
Monitor the wireless environment:
while (true) do
    Periodically monitor the wireless environment
    if (a change is identified) then
        Update t_r
        Restart Learning procedure
    end
end
```

is transmitted in the unlicensed spectrum, while the LTE UL traffic, the LTE control signals and the Hybrid Automatic Repeat Request (HARQ) are maintained in the licensed band of the operator.

Regarding the Wi-Fi network, 802.11n mode has been selected for the simulation model. This mode allows operation in 5 GHz unlicensed band. Additionally, it is assumed that frame aggregation is disabled, so that only a single packet is transmitted after the channel is estimated as idle. Table 6.2 presents the system parameters that have been used for Wi-Fi.

The average backoff time for a Wi-Fi transmission can be expressed as:

$$T_{\text{Av\_BO}} = CW_{\text{min}} \times \frac{ts}{2} \tag{6.16}$$

Additionally, the duration of the acknowledgment is given by:

$$T_{\text{ack}} = T_{\text{plcp}} + \left\lceil \frac{L_{\text{s}} + L_{\text{ack}} + L_{\text{t}}}{n_{\text{sym}}} \right\rceil \times T_{\text{sym}} \tag{6.17}$$

The duration (T_{plcp}) of Physical Layer Convergence Protocol (PLCP) is $20\mu s$ and corresponds to $8\mu s$ for the Short Training Field (STF), $8\mu s$ for the Long Training Field (LTF) and $4\mu s$ for the SIGNAL field.

The duration of a data-packet transmission is given by:

$$T_{\text{data}} = T_{\text{plcp}} + \left\lceil \frac{L_{\text{s}} + L_{\text{MAC\_h}} + D + L_{\text{t}}}{n_{\text{sym}}} \right\rceil \times T_{\text{sym}} \tag{6.18}$$

Hence, the total duration of a successful Wi-Fi transmission can be expressed as:

$$T_{\text{suc}} = T_{\text{DIFS}} + T_{\text{Av\_BO}} + T_{\text{SIFS}} + T_{\text{ack}} + T_{\text{data}} \tag{6.19}$$

For both mLTE-U and Wi-Fi networks 20 MHz of bandwidth is used. For Wi-Fi, 64-Quadrature Amplitude Modulation (QAM) modulation scheme and 3/4 coding scheme has been used that correspond to the 6th Modulation and Coding Scheme (MCS) Index [7]. On the other hand, for mLTE-U transmission in the

Table 6.2: Wi-Fi simulation parameters

Parameter	Value
Wi-Fi mode	802.11n
Frame aggregation	no
Bandwidth	20 MHz
DIFS duration	34 μs
SIFS duration	16 μs
Timeslot duration (ts)	9 μs
PLCP preamble + Headers Duration (T_{plcp})	20 μs
PLCP service field (L_s)	16 bits
MAC header (L_{MAC_h})	224 bits
Tail bits (L_t)	6 bits
ACK length (L_{ack})	112 bits
Payload (D)	12000 bits
OFDM Symbol duration (T_{sym})	4 μs
Number of bits per OFDM symbol (n_{sym})	216 bits
CW_{min}	15
CW_{max}	1023
RTS/CTS	no

unlicensed spectrum, the transmission data rate is equal to 150 Mbps. This corresponds to 2x2 MIMO, 64-QAM, 28th MCS Index and 26th Transport Block Size (TBS) Index, as it is defined in 3GPP specs 36.213 [5].

During the simulation, it is assumed that all the nodes for both mLTE-U and Wi-Fi networks are in the proximity of each other. This way, during every transmission the ED threshold is surpassed and the backoff mechanisms of mLTE-U and Wi-Fi are triggered. The ED threshold of the mLTE-U CCA mechanism is equal to the ED threshold of Wi-Fi.

Concerning the Q-learning parameters, they are listed in Table 6.3. The ϵ parameter initially takes a high value (e.g. 1) in order to explore fast new states. As the number of iterations increases and all or most of the states are reached at least once, the ϵ value decreases by p_ϵ, until a minimum value of ϵ is reached (m_ϵ). During the simulations, the number of iterations before ϵ decreases is computed

Table 6.3: Q-learning simulation parameters

Parameter	Value
range of ϵ value	$[1-0.05]$
learning rate (η) value	0.7
discount factor (γ) value	0.9
rate of ϵ reduction (p_ϵ)	0.05
minimum value of ϵ (m_ϵ)	0.05
number of iterations before reduction of ϵ (i_ϵ)	399
throughput tolerance (ζ) value (Mbps)	3
fraction of positive rewards (β) value	0.2
maximum iteration number	10000

as:

$$\begin{aligned} i\_\epsilon = (TXOP_{max} - TXOP_{min} + 1)\times \\ (muting_{max} - muting_{min} + 1) \end{aligned} \tag{6.20}$$

that corresponds to the total number of the possible states.

6.8 Performance evaluation

6.8.1 Standalone operation for mLTE-U and Wi-Fi

This section presents the performance of the designed system, when mLTE-U and Wi-Fi operate in standalone mode. Thus, they do not need to compete for the wireless medium with other co-located networks. Both mLTE-U and Wi-Fi networks consist of one base station and one end-device.

Fig. 6.4 illustrates the obtained DL throughput results of mLTE-U network in standalone mode. The x-axis holds the different muting period configurations in ms ranging from $0ms$ to $20ms$. The different TXOP durations in ms ranging from $2ms$ to $20ms$ are representing with different colors. Finally, the y-axis shows the obtained throughput in Mbps for every possible combination of TXOP and muting period.

From the figure, it is clear that the throughput for every different TXOP decreases as the duration of the muting period increases. Of course, this is to be expected as a higher muting period increases the idle period of an eNB. Respectively, it can be seen that for a specific muting period, the obtained throughput increases as the TXOP increases. As the TXOP duration increases, the mLTE-U

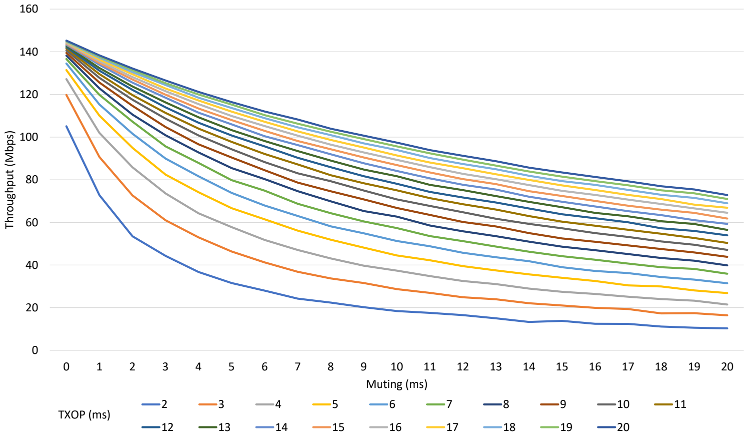

Figure 6.4: Throughput of mLTE-U for the different TXOP and muting period configurations, during the standalone scenario

has to perform less often a CCA procedure before it transmits again. This has an impact on the obtained throughput, as for higher TXOP the eNB spends less time evaluating the channel compared to a scenario in which a lower TXOP duration is used.

Hence, the minimum obtained throughput corresponds to an mLTE-U configuration, in which TXOP has the smallest value ($2ms$) and it is followed by a muting period of the longest duration ($20ms$). On the contrary, the maximum obtained throughput can be achieved when the maximum TXOP is used ($20ms$) followed by the minimum muting period ($0ms$).

According to the simulation results and after the introduction of CCA, the highest throughput value of mLTE-U for $TXOP = 20ms$ and $muting = 0ms$ is $145.28Mbps$. This value will be used for the computation of the target mLTE-U throughput in (6.10) that is used by the Q-learning algorithm. Regarding the Wi-Fi network, the obtained standalone throughput is stable over time and corresponds to $30.8Mbps$.

6.8.2 mLTE-U and Wi-Fi coexistence

In this section, coexistence scenarios between mLTE-U and Wi-Fi of high interest are discussed. This will help the reader to understand the role of Q-learning in selecting the mLTE-U configurations that can offer fair coexistence with other co-located networks. Further details on the coexistence between mLTE-U and Wi-Fi can be found in [9].

6.8.2.1 Evaluation of single mLTE-U and single Wi-Fi coexistence

In this scenario, one mLTE-U network coexists with one Wi-Fi network. The mLTE-U network consists of one eNB and one UE, while the Wi-Fi network consists of one AP and one STA. Both networks transmit only DL traffic. Fig. 6.5 depicts the mLTE-U throughput and Fig. 6.6 the Wi-Fi throughput for every possible combination of TXOP and muting period. In both figures, the x-axis holds the different muting period configurations in ms. The different TXOP configurations (in ms) are depicted with different colors. The y-axis presents the obtained throughput in Mbps for every combination of TXOP and muting period.

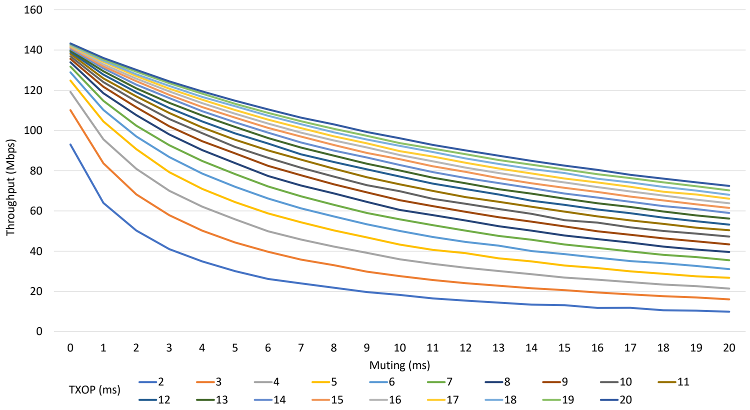

Figure 6.5: Throughput of mLTE-U during the single mLTE-U and single Wi-Fi coexistence scenario

As it can be observed and similar to the standalone scenario, the mLTE-U throughput increases as the TXOP increases. Also, a shorter muting period offers higher throughput compared to a longer one as mLTE-U can compete more often for accessing the medium. Furthermore, the throughput values are slightly lower compared to the standalone scenario. This occurs due to the co-located Wi-Fi network that competes for the medium and eventually gains access to it. On the other hand, the Wi-Fi throughput increases when the muting period of mLTE-U increases. This is to be expected, as Wi-Fi can exploit the muting period for further transmissions. Additionally, the Wi-Fi throughput is inversely proportional to the TXOP of mLTE-U. During a short TXOP, Wi-Fi has more often opportunities to compete for the medium and access it compared to a longer TXOP during which mLTE-U occupies the medium for longer period of time.

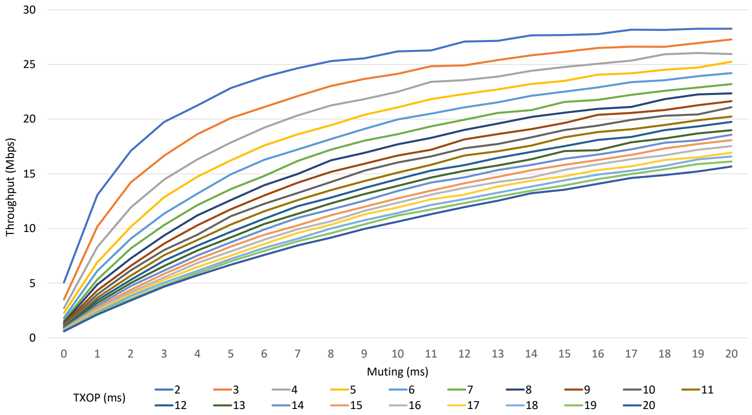

Figure 6.6: Throughput of Wi-Fi during the single mLTE-U and single Wi-Fi coexistence scenario

6.8.2.2 Evaluation of multiple mLTE-U and multiple Wi-Fi coexistence

In this scenario, multiple mLTE-U and multiple Wi-Fi networks coexist among each other. More specifically, three mLTE-U networks coexist with three Wi-Fi networks creating this way a dense wireless environment. Each one of the mLTE-U and Wi-Fi networks consists of one base station and one end-device. Each network transmits only DL traffic. Similarly to the previous subsection (6.8.2.1), Fig. 6.7 and Fig. 6.8 show the mLTE-U combined throughput and the Wi-Fi combined throughput respectively.

Fig. 6.8 clearly indicates that the performance of the Wi-Fi networks is severely impacted by the co-located mLTE-U networks for most of the mLTE-U configurations. Only when mLTE-U is configured with a short TXOP that is followed by a relatively long muting period, the combined throughput of Wi-Fi is improved. In case of multiple mLTE-U nodes, there is a high possibility that a muting period of an mLTE-U network is exploited by the TXOP of another mLTE-U network. This impact becomes higher when the mLTE-U networks are configured to use a high TXOP duration combined with a low muting period. However, when the mLTE-U networks use a short TXOP and a high muting period, they remain silent simultaneously for a longer period and Wi-Fi can exploit the remaining muting period in order to transmit. Furthermore, in case of multiple Wi-Fi networks the exploitation of a muting period is less optimal as they compete among each other to access the medium.

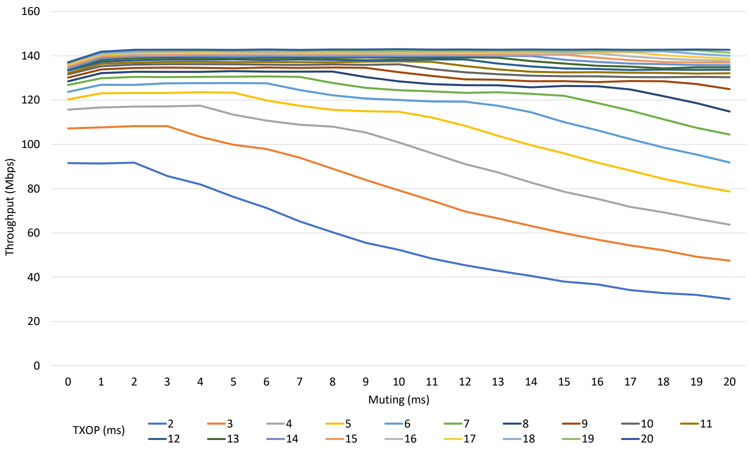

Figure 6.7: Combined throughput of mLTE-U during the multiple mLTE-U and multiple Wi-Fi coexistence scenario

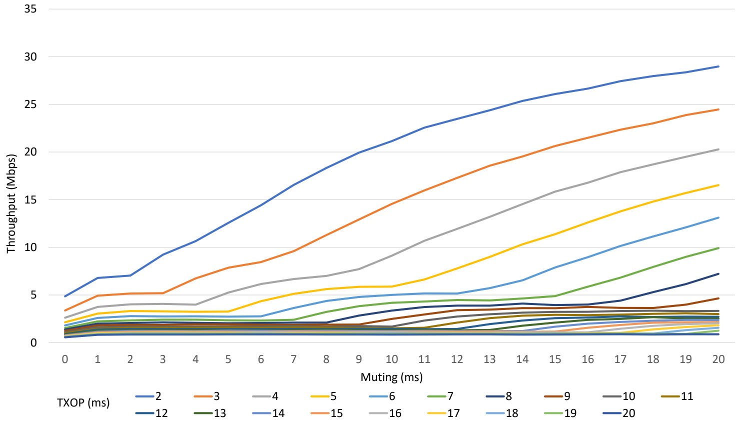

Figure 6.8: Combined throughput of Wi-Fi during the multiple mLTE-U and multiple Wi-Fi coexistence scenario

6.8.3 Fair coexistence using Q-learning

As shown in the previous subsection, the performance of coexisting mLTE-U and Wi-Fi networks depends on the density of the environment, as well as on the configuration of mLTE-U. The numerous combinations of TXOP and muting period offer different coexistence conditions that vary based on the number of co-located networks. As a wireless environment is dynamic and new networks are activated and deactivated often, it is important for a coexistence scheme to be self-adaptive. This section discuses the way that Q-learning technique, as it has been discussed in Section 6.6, can assist an mLTE-U network in optimally selecting the TXOP and muting period in order to provide fair coexistence with other co-located wireless technologies in unlicensed spectrum.

6.8.3.1 Q-learning for single mLTE-U and single Wi-Fi coexistence

Fig. 6.9 illustrates the convergence of the Q-learning algorithm during the scenario in which one mLTE-U network coexists with one Wi-Fi network, similar to Section 6.8.2.1. On the horizontal axis is the number of iterations and on the vertical axis is the sum of the values in the Q matrix. When the sum of the Q matrix converges, the agent has learned the current environment and can perform the optimal actions in any state.

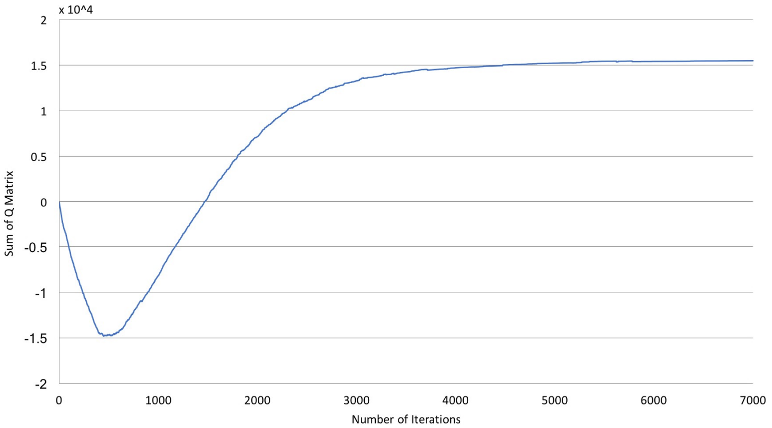

Figure 6.9: Convergence of Q matrix sum during the learning process for the single mLTE-U and single Wi-Fi scenario

It can be observed that in the beginning of the learning process the sum of Q matrix decreases. This occurs as initially due to the high degree of exploration, the agent (mLTE-U eNB) tries many different states. Most of these states do not offer the desired fairness. This way the agent receives low rewards. As the learning continues, the agent locates the states that can provide fair coexistence with the Wi-Fi network, increasing the received reward. After a sufficient amount of iterations (e.g. 3000), it can be seen that the agent has learned the configurations that can lead to fair coexistence and the sum of Q matrix starts converging.

Fig. 6.10 presents the throughput of mLTE-U and Wi-Fi for the selected by Q-learning configurations (TXOP and muting period) and for the same scenario as above, where one mLTE-U network coexists with one Wi-Fi. The TXOP and muting period configurations that have been learned by Q-learning are able to provide to the mLTE-U network a throughput that is in the desired range of $Thr_{target}^{mLTE-U} \pm \zeta$, where in the specific scenario and from (6.10) $Thr_{target}^{mLTE-U} = 72.64Mbps$ and $\zeta = 3Mbps$. As can be seen from the results, all the selected configurations are capable to provide the desired fair coexistence with Wi-Fi, as the co-located Wi-Fi network is able to obtain a throughput close to $15Mbps$. Hence, both networks can achieve half of the throughput that can be reached during the respective standalone operation.

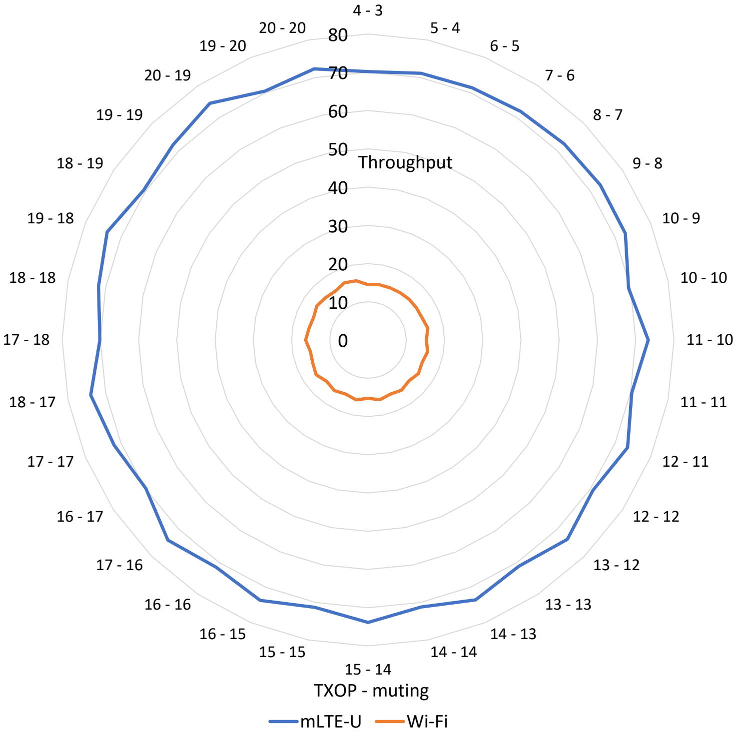

Figure 6.10: Throughput of mLTE-U and Wi-Fi for the selected by Q-learning configurations of TXOP and muting period during the single mLTE-U and single Wi-Fi scenario

Based on the traffic requirements that an eNB must satisfy, it can select the appropriate configuration among the ones that have been identified by the Q-learning procedure and can provide fair coexistence with the co-located networks. For instance, in case of voice traffic (AC_VO), an mLTE-U network can select a configuration that requires a shorter muting period. On the other hand, when best effort traffic (AC_BE) must be served, an mLTE-U network can select a configuration that offers a longer muting period combined with a shorter TXOP.

6.8.3.2 Q-learning for multiple mLTE-U and multiple Wi-Fi coexistence

Fig. 6.11 presents the convergence of the Q-learning algorithm for the coexistence scenario similar to Section 6.8.2.2, in which three mLTE-U networks and three Wi-Fi networks coexist with each other.

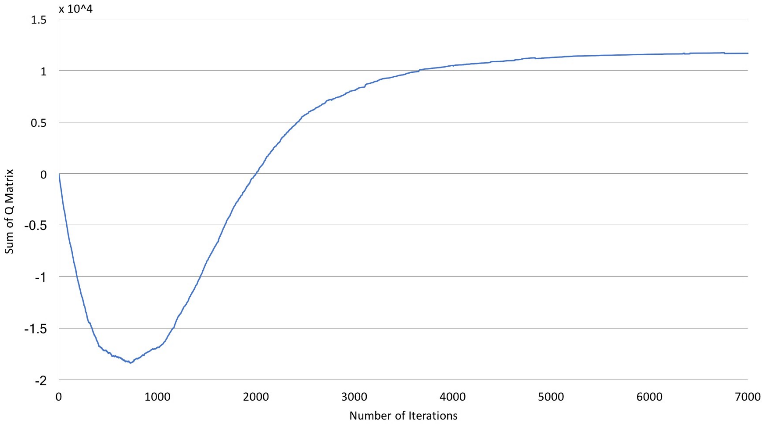

Figure 6.11: Convergence of Q matrix sum during the learning process for the multiple mLTE-U and multiple Wi-Fi scenario

By observing Fig. 6.9 and Fig. 6.11, it can be seen that in case of multiple mLTE-U and Wi-Fi networks (Fig. 6.11) the sum of the Q matrix initially decreases in a higher grade compared to the case of a single mLTE-U and Wi-Fi network (Fig. 6.9). In the case of multiple mLTE-U and Wi-Fi networks, many co-located networks have to gain equal access to the medium. Hence, the mLTE-U configurations that can offer fair coexistence are limited compared the configurations of the single mLTE-U and Wi-Fi network. For this reason, during the first iterations of Q-learning, an agent will explore more states that give a negative reward, which entails a reduced sum of Q matrix. As the agent learns the environment and approaches the target, it chooses states that can give high reward, increasing the sum of Q matrix, until it finally converges.

Fig. 6.12 illustrates the TXOP and muting period configurations that can offer fair coexistence during this dense scenario, as they have been selected by the Q-learning mechanism. As discussed, it can be observed that compared to the single mLTE-U and single Wi-Fi scenario, the desired combinations are fewer due to the multiple coexisting networks.

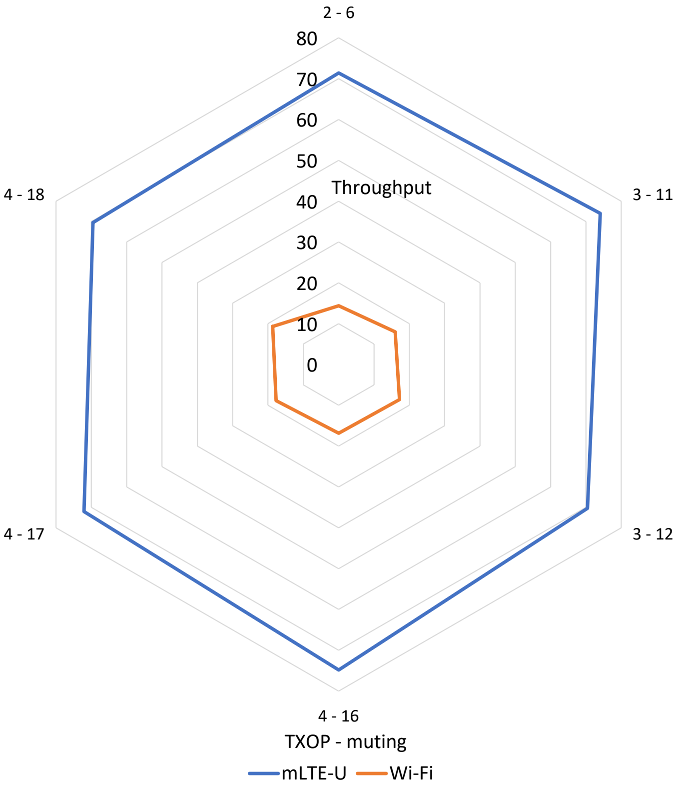

Figure 6.12: Throughput of mLTE-U and Wi-Fi for the selected by Q-learning configurations of TXOP and muting period during the multiple mLTE-U and multiple Wi-Fi scenario

6.8.3.3 Further discussion

Q-learning is fundamentally designed to be able to adapt to the changes of the environment. This way, an agent can update the Q-table and learn new optimal actions towards the achievement of its target. Regarding the mLTE-U scheme, a change in the status of the wireless environment can be identified using a technology recognition scheme. Such change can be the activation of a new network or the deactivation of a previously active network.

Fig. 6.13 shows the convergence of Q-learning for a scenario in which initially one mLTE-U network coexists with one Wi-Fi network and at some point a second mLTE-U network is activated. As it can be seen, the first part of the diagram is similar to the one that is depicted in Fig. 6.9, as only one mLTE-U network coexists with one Wi-Fi. After the 7000th repetition, a new mLTE-U network is activated. Then, an agent starts identifying the new mLTE-U parameters that can offer fair coexistence regarding the new conditions in the wireless environment using Q-learning. At this point, the ϵ value of the $\epsilon-$greedy exploration strategy is reset to 1. As shown in Fig. 6.13 the sum of Q matrix starts decreasing as new states are explored and in most of the cases they do not meet the new target that is computed by (6.10). Thus, an agent receives often negative reward. As the amount of iterations increases and an agent learns the new environment, the cumulative reward increases and finally converges again.

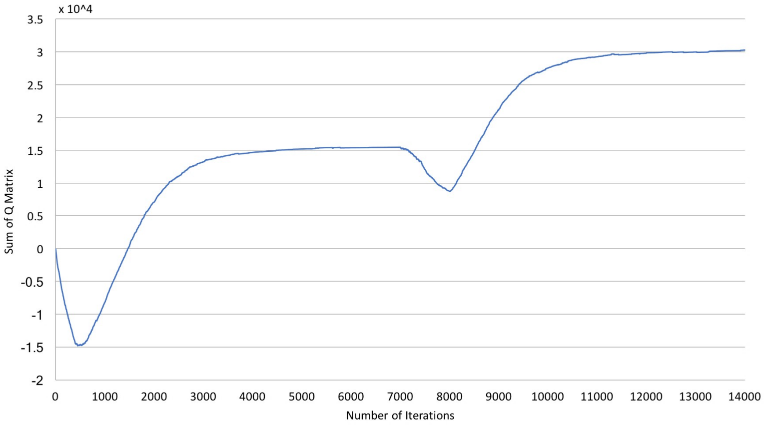

Figure 6.13: Convergence of Q matrix sum during the learning process and adaptation to the changes of the wireless environment

As can be seen, the integration of Q-learning in the mLTE-U scheme can be of great importance towards the provision of fair coexistence between LTE and Wi-Fi in unlicensed spectrum. Q-learning can render an mLTE-U network capable to operate autonomously by learning and adapting into a dynamic wireless environment.

6.8.4 Comparison of the proposed Q-learning with conventional selection schemes

In this section, we compare the coexistence of mLTE-U with Wi-Fi, when mLTE-U selects the optimal configuration parameters using Q-learning with the case that mLTE-U is configured using conventional selection schemes, such as random and round-robin selection. According to the random selection scheme, mLTE-U configures the TXOP and muting period by selecting random values. For this scheme, uniformly distributed random selection is used. When round-robin is used, mLTE-U selects consecutively all the different configurations of TXOP and muting period. Such conventional mechanisms require lower complexity than Q-learning, as Q-learning must first learn the environment in order to offer optimal configurations. For this comparison and similar to Section 6.8.2.1, we consider a scenario, in which one mLTE-U network coexists with one Wi-Fi network.

Fig. 6.14 presents the histogram of mLTE-U and Wi-Fi throughput for all the examined selection mechanisms. Fig. 6.14 (a) and Fig. 6.14 (d) show the respective histogram of the mLTE-U and Wi-Fi throughput according to the Q-learning mechanism. Fig. 6.14 (b) and Fig. 6.14 (e) present respectively the histogram of mLTE-U and Wi-Fi throughput when random selection mechanism is used and Fig. 6.14 (c) and Fig. 6.14 (f) illustrate the histogram of the corresponding mLTE-U and Wi-Fi throughput when round-robin selection mechanism is used. For every scenario, the throughput is calculated for the same number of iterations (7000 iterations). In every figure, the x-axis holds the obtained throughput value in Mbps, classified into series of intervals. The y-axis holds the frequency of the throughput value, meaning in how many iterations the obtained throughput value was in a specific interval.

As can be observed, in both random and round-robin mechanisms, the obtained throughput of mLTE-U and Wi-Fi is spread over all the possible values of the throughput that can be achieved by each network. This is related to the nature of the selection schemes, as the random scheme chooses in every interval a random pair of TXOP and muting period, while the round-robin scheme selects consecutively all the available combinations (serially one pair in each interval). Furthermore, in Fig. 6.14, it can be seen that the histograms of the random and the round-robin mechanisms are similar. This is related to the high number of iterations. In a long term basis and due to the uniformly distributed randomness, the random scheme selects every combination of TXOP and muting period for almost equal amount of times.

The supremacy of the proposed Q-learning scheme over the conventional schemes can be clearly seen in the graphs (a) and (d). As shown, using Q-learning the mLTE-U network learns the optimal configuration parameters that offer fair coexistence with the co-located Wi-Fi network. During the first iterations of Q-learning that correspond to the exploration phase the obtained throughput of mLTE-U and Wi-Fi varies, as very often random actions are chosen due to the high ϵ value. As the agent learns the environment and the value of ϵ decreases, the exploitation phase increases. As result, the agent chooses more and more often configuration values that approach the target value (Thr_{target}^{mLTE-U}) of the mLTE-U throughput. Hence, the dominant majority of the obtained mLTE-U throughput

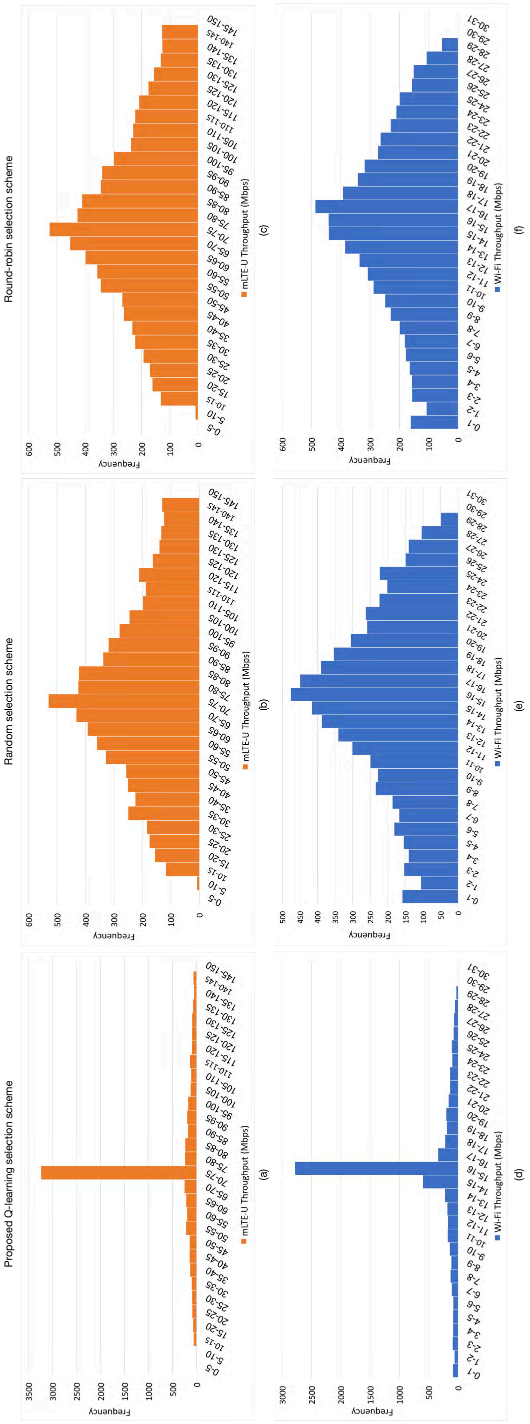

Figure 6.14: Throughput histogram of mLTE-U and Wi-Fi for the proposed Q-learning, random and round-robin selection schemes

approaches its target value ($72.64Mbps$), offering fair coexistence to Wi-Fi that achieves also half of its maximum throughput ($15.4Mbps$).

6.9 Conclusion

In our days and towards 5G, the number of heterogeneous networks increases rapidly. These networks consist of diverse wireless technologies with different requirements. The introduction of LTE-U has pushed the wireless community to find solutions that can enable fair coexistence of LTE with other well-established technologies in unlicensed spectrum. Towards a global solution that respects the regional requirements worldwide, 3GPP announced the LTE LAA standard according to which, LTE can operate in unlicensed spectrum through a secondary cell and by performing a CCA procedure before a transmission.

However, the ratio of transmission opportunities between LTE LAA and Wi-Fi is not balanced, especially in the case that Wi-Fi does not use frame aggregation. In order to enhance the fairness of LTE-U, an adaptable scheme named mLTE-U has been proposed. According to mLTE-U, LTE can transmit in unlicensed spectrum using an adaptable TXOP after a successful CCA. A TXOP is followed by an adaptable muting period. This muting period can be exploited by other co-located networks in order to gain access to the wireless medium.

In this article, we analytically study the mLTE-U scheme. The system model of mLTE-U, when it coexists with Wi-Fi is analyzed. Additionally, we introduce a Q-learning technique that can be used by an mLTE-U network to learn the wireless environment and autonomously select the TXOP and muting period configurations that can provide fair coexistence with other co-located technologies. Simulation results show how Q-learning can assist mLTE-U to find optimal configurations and be adapted to changes of the wireless environment providing the desired fair coexistence. Furthermore, the proposed scheme is compared with conventional selection schemes, revealing its supercity in providing fair coexistence with Wi-Fi.

In the near future, this work can be extended by exploiting deep Q-learning using neural networks, towards optimal selection of the mLTE-U parameters that can offer fair coexistence between mLTE-U and other co-located wireless technologies.

Acknowledgment

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7

Enhancing the Coexistence of LTE and Wi-Fi in Unlicensed Spectrum Through Convolutional Neural Networks

The shared spectrum is a non-deterministic and dynamically changing environment. These changes refer to the type and number of co-located wireless networks, the number of the active users of each network and the type of traffic that each user transmits. Hence, such information should be taken into account by a coexistence mechanism in order to be adapted to potential changes of the wireless environment. Towards this direction, this chapter presents a Convolutional Neural Network (CNN) that can be used to identify LTE and Wi-Fi transmissions. The proposed CNN is also able to identify hidden terminal effect from multiple LTE, multiple Wi-Fi and concurrent LTE and Wi-Fi transmissions. The CNN is trained and validated for different wireless signal representations and for different Signal to Noise Ratio (SNR) values. The identified transmissions can be used to compute the channel occupancy by each technology. This information can be exploited by the muting LTE-U (mLTE-U) scheme that has been studied in Chapters 5 and 6 in order to select the TXOP and muting period configurations that provide fair coexistence to co-located mLTE-U and Wi-Fi networks.

⋆ ⋆ ⋆

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Journal (To be submitted).

Abstract Over the last years, the ever-growing wireless traffic has pushed the mobile community to investigate solutions that can assist in a more efficient management of the wireless spectrum. Towards this direction, the Long Term Evolution (LTE) operation in unlicensed spectrum has been proposed. Targeting a global solution that respects the regional requirements, 3GPP announced the standard of LTE Licensed Assisted Access (LAA). According to LTE LAA, when LTE gets access to the medium, it can transmit for a predefined transmission opportunity (TXOP) that depends on the priority class that is used. This may cause coexistence issues between LTE and Wi-Fi, especially when the latter does not use frame aggregation. Targeting a technique that enables fair channel access, we have proposed mLTE-U. According to mLTE-U, LTE uses a variable TXOP, followed by a variable muting period that can be used by other co-located networks to get access to the medium. However, in order to select the appropriate mLTE-U configuration, information about the dynamically changing wireless environment is required. To this end, this article proposes a Convolution Neural Network (CNN) that is trained to perform identification of LTE and Wi-Fi transmissions. Additionally, it can identify hidden terminal effect caused by multiple LTE transmissions, multiple Wi-Fi transmissions or concurrent LTE and Wi-Fi transmissions. The designed CNN has been trained and validated using Commercial Off-The-Shelf (COTS) LTE and Wi-Fi hardware equipment and for two wireless signal representations, namely In-phase and Quadrature (I/Q) samples and frequency domain representation through Fast Fourier Transform (FFT). The classification accuracy of the two resulting CNNs is tested for different Signal to Noise Ratio (SNR) values. The experimentation results show that the data representation affects the accuracy of the CNN. Especially for low SNR values, the data representation in frequency domain outperforms the I/Q data representation. However, classification based on I/Q samples can be done immediately without requiring any additional step. The obtained information from the CNN can be exploited by the mLTE-U scheme in order to provide fair coexistence between the two wireless technologies.

7.1 Introduction

Over the last years, the wireless transmitted traffic has been increased tremendously, as a result of the unparalleled technological growth. Mobile communications have transformed the way people communicate, exchange information and experience entertainment. According to the International Telecommunication

Union Radiocommunication Sector (ITU-R), in May 2015, over the world's population of 7.3 billion, there were about 7.5 billion mobile subscriptions worldwide and about 3.7 billion people connected [1]. It is estimated that the mobile traffic will grow at an annual rate of around 54% between 2020 and 2030. Additionally, Huawei predicts that by 2025 consumers worldwide will collectively be using 40 billion connected devices [2]. This massive amount of devices communicate using different types of wireless technologies such as Long Term Evolution (LTE), IEEE 802.11 (Wi-Fi), IEEE 802.15.4 and Bluetooth. Recently, high frequency bands (mmWave) are used for multi-gigabit speeds (IEEE 802.11ad), while sub-GHz bands are exploited by technologies that target low power and wide range communications such as LORA and SIGFOX. It becomes clear that soon the wireless network capacity will become a bottleneck for serving the wireless traffic.

The LTE operation in the unlicensed spectrum has emerged as a promising and effective solution that can assist in exploiting the wireless spectrum in a more efficient way [3]. Hence, it has attracted significant attention from the wireless community that has introduced several techniques aiming to enable harmonious coexistence between LTE and other well-established technologies in the unlicensed spectrum, such as Wi-Fi [4].

There are three dominant approaches for LTE operation in unlicensed spectrum according to the regional regulations and the desired deployment scenario. In regions where a Listen Before Talk (LBT) procedure before a transmission is not mandatory by the regional regulations, such as in U.S.A. or in China, it has been proposed that LTE can transmit in unlicensed frequencies using a duty-cycle technique. Carrier Sense Adaptive Transmission (CSAT) [5] is the most prominent technique of this nature. It has been proposed by Qualcomm and builds on elements of LTE Release 12 [6].

On the other hand, 3GPP published the LTE Licensed Assisted Access (LTE LAA) standards as part of the Release 13 [7] and Release 14 [8]. Through LTE LAA, 3GPP aims for a coexistence technique that respects the regional regulations worldwide, including regions where an LBT procedure before a transmission in the unlicensed spectrum is mandatory, such as in Europe and in Japan.

Both the aforementioned solutions require that an operator owns a licensed frequency band and opportunistically offloads LTE traffic in the unlicensed spectrum. In order to decouple LTE from the operators and enable the LTE operation solely in the unlicensed spectrum, leading wireless stakeholders formed the MulteFire Alliance [9]. MulteFire LTE builds on elements of LTE LAA and combines the high performance of LTE with the simple deployment of Wi-Fi. Thus, MulteFire LTE can be deployed by cable companies, Internet Service Providers (ISPs), operators, building owners and enterprises.

In our previous work [10], we observed that the LTE LAA standard defines that a Clear Channel Assessment (CCA) procedure must be performed before any transmission in the unlicensed spectrum; this is being done according to four channel access priority classes. Each of these classes defines among others the transmission duration in the unlicensed channel after it has been accessed as idle. This duration varies from $2ms$ up to $10ms$. This behavior can cause unfair coexistence with a typical Wi-Fi transmission that lasts for a few hundreds of μs when frame aggregation is not enabled or supported by the 802.11 standard [11]. Based on this observation and in order to enable harmonious and fair coexistence between LTE and Wi-Fi, we proposed a novel coexistence mechanism named mLTE-U. mLTE-U builds on elements of LTE Release 13. It requires an LBT procedure before a transmission in unlicensed spectrum. mLTE-U is an adaptive LTE transmission scheme according to which LTE can transmit in the unlicensed spectrum for a variable transmission opportunity (TXOP) period, after the medium has been assessed as idle. The TXOP is followed by a variable muting period. This muting period can give channel access opportunities to other co-located networks such as Wi-Fi. The selection of the appropriate combinations of TXOPs and muting periods must be done in a way that the co-located networks share the medium in a fair manner. In [12], we further extended our previous work by introducing a Q-learning procedure that is able to provide automatic and autonomous selection of the appropriate TXOP and muting period combinations that can enable fair coexistence between the co-located networks.

However, as we discussed in [10], in order to enable fair coexistence, different types of information from the wireless environment should be known, such as the the type of the co-located networks, the number of the transmitting nodes and the load of each node. Towards this direction, this article introduces a Convolutional Neural Network (CNN) that can be used to enable the transmission identification of co-located LTE and Wi-Fi networks. The trained CNN can be used to identify LTE and Wi-Fi transmissions. Additionally, it can identify hidden terminal effect that is caused by multiple LTE transmissions, multiple Wi-Fi transmissions and concurrent LTE and Wi-Fi transmissions. The designed CNN has been trained and validated for the following two wireless signal representations: Inphase and Quadrature (I/Q) samples and frequency domain representation through Fast Fourier Transform (FFT). The classification accuracy is tested for variable Signal to Noise Ratio (SNR) values. For the purposes of this study, COTS LTE and Wi-Fi hardware equipment has been used. The transmission identification can be exploited in order to compute the channel access occupancy of each technology and select the appropriate mLTE-U configurations that offer fair coexistence in the unlicensed spectrum.

The main contribution of this work is summarized as follows:

- A brief introduction to CNN is provided in order to give to the reader the necessary background of the topic.

- A CNN has been designed and trained to be able to identify LTE and Wi-Fi transmissions.
- Interfering LTE and Wi-Fi transmissions, as the result of a hidden terminal, can be identified. These interfering transmissions include concurrent LTE transmissions, concurrent Wi-Fi transmissions and simultaneous LTE and Wi-Fi transmissions.
- For the training and validation of the CNN, COTS hardware and open-source software have been used. This way, real I/Q LTE and Wi-Fi samples were retrieved from the wireless medium.
- The designed CNN has been trained and validated using two wireless signal representations: I/Q samples and frequency domain representation through FFT.
- The classification accuracy of the trained CNNs is tested for various SNR values.
- The extracted information by the CNN is exploited by mLTE-U scheme to enhance the coexistence between LTE and Wi-Fi in unlicensed spectrum.

The remainder of the article is organized as follows. Section 7.2 gives an overview of the current literature on the coexistence of LTE and Wi-Fi. Additionally, it presents several use-cases of deep learning on wireless networks. In Section 7.3, we give a brief introduction to CNN, their constituent elements and the relevant terminology. Then, Section 7.4 describes the hardware and software equipment that has been used to train and validate the designed CNN, as well as the CNN implementation details. Section 7.5 presents the structure of the CNN network and the performance metrics that have been used in the context of this article. Furthermore, the section evaluates the performance of the designed CNN for each signal representation and discusses the obtained experimentation results. Section 7.6 presents how the CNN can be exploited by mLTE-U scheme in order to enhance the coexistence between co-located LTE and Wi-Fi networks. Finally, Section 7.7 concludes the article and discusses plans for future work.

7.2 Related Work

7.2.1 LTE and Wi-Fi coexistence

When the idea of LTE operating in unlicensed spectrum was initially introduced, there were serious concerns about unfair coexistence between LTE and other well-established technologies in unlicensed spectrum, such as Wi-Fi. These concerns lie in the fact that LTE has been designed to be a scheduled technology operating in a licensed band, meaning that it does not estimate the availability of the wireless channel before a transmission. As a result, arbitrary transmissions could force the networks in its proximity to continuously backoff. In our previous work [13], we investigated the impact of a traditional LTE network operating in unlicensed spectrum on Wi-Fi. For the purposes of this study COTS hardware has been used at the LTE testbed of IMEC [14]. The study examines three different levels of LTE signal power, each one representing different possible levels of LTE impact on Wi-Fi. The results show that the performance of Wi-Fi can be significantly affected by LTE. This has been verified by several other studies [15] [16] [17] that evaluate the impact of LTE on Wi-Fi through experiments, mathematical analysis and simulations. The results make clear that coexistence mechanisms are required in order to enable fair and harmonious spectral sharing between LTE and other co-located technologies such as Wi-Fi.

Over the last years, several coexistence mechanisms have been proposed, aiming to enable the desired coexistence between LTE and Wi-Fi. A detailed survey of the coexistence between LTE and Wi-Fi on $5GHz$ together with the corresponding deployment scenarios is given in [18]. The survey describes in detail the coexistence-related features of LTE and Wi-Fi, the coexistence challenges, the differences in performance between the two wireless technologies and co-channel interference. The authors present in detail the coexistence techniques that have been proposed in the literature and they analyze the concept of scenario oriented coexistence. According to this concept, coexistence related problems can be solved based on different deployment scenarios.

In our previous work [19], the LTE operation in unlicensed spectrum has been extensively studied. The article provides a detailed analysis of the current state-of-the-art of LTE and Wi-Fi coexistence. Additionally, it introduces a classification of techniques that can be applied between co-located LTE and Wi-Fi networks. The study of the literature together with the classification revealed the lack of cooperation schemes between LTE and Wi-Fi that can lead to more optimal use of the wireless resources. In order to fill this gap, we proposed several concepts of cooperation techniques that can enhance the spectral efficiency of co-located LTE and Wi-Fi networks. The proposed methods are compared between each other in terms of complexity and performance.

Similar to the CSAT mechanism as described in Section 7.1, the authors in [20] describe a coexistence mechanism that exploits periodically blank subframes during an LTE frame. These frames can be used by Wi-Fi to gain access to the medium. Simulation results show that the number and the order of the black subframes have an impact on the performance of the provided coexistence.

A coexistence scheme in order to be applicable globally must incorporate, among others, a channel estimation mechanism that will be used to ensure the availability of the wireless medium before a transmission. Following this approach and as it has been described in Section 7.1, 3GPP announced the LTE LAA as part of Release 13 [7]. According to the LTE LAA standard, a CCA procedure must be performed before every transmission in the unlicensed spectrum.

The concept of a channel estimation procedure by LTE as a coexistence enabler mechanism has been proposed in several works. In [21], the authors propose an LBT scheme for LTE that comprises of two parts, named on-off adaptation for channel occupancy time and short-long adaptation for idle time. According to the first part, the LTE occupancy time is adapted based on the load of the network. Concerning the second part, the idle period is adapted based on the Contention Window (CW) duration of Wi-Fi. The authors in [22], propose an LBT Category 4 (Cat 4) channel access scheme for LTE. The proposed LBT scheme uses an adaptive CW size for LTE LAA. The simulation results show that it can achieve higher performance compared to the fixed CW size approach.

7.2.2 Deep Learning for Wireless Networks

Over the last years, deep learning has been widely used in the domains of computer vision (image recognition and image classification) [23] and language processing (speech recognition and translation) [24] [25]. Importantly, the performance of the deep learning algorithms in these applications has become remarkable, reaching or even surpassing human levels of accuracy [26]. Inspired by that, wireless communication engineers have started adopting neural networks (NN) in order to enhance applications in wireless networks such as channel prediction, decoding, quantization, modulation recognition, technology recognition and more [27].

The work presented in [28] was one of the first approaches in this domain. The authors propose a CNN trained based on I/Q data for radio modulation classification. The proposed solution is compared with traditional methods based on expert features such as cyclic-moment based features and conventional classifiers, such as Decision Tree, K=1-Nearest Neighbor, Gaussian Naive Bayes, Support Vector Machines (SVM) as well as a deep neural network consisting only of Fully Connected (FC) layers. They show how the proposed solution outperforms the traditional methods especially at low SNR.

The authors in [29] propose a CNN system that is able to identify eight different kinds of signals. They describe the appropriate architecture that renders the CNN classifier effective for the proposed system. Choi-Williams time-frequency distribution (CWD) transformation is used in order to obtain the image features into the CNN. Simulations are used to measure the identification performance of the proposed framework. The simulations results show that the overall ratio of successful recognition (RSR) is 93.7% when the SNR is higher or equal to $-2dB$.

In [30], the authors present a framework for end-to-end learning from spectrum data, which is a deep learning based unified approach that enables various wireless signal identification tasks. The article gives a brief overview of machine learning, deep learning and CNNs and proposes a reference model for their application for spectrum monitoring. The authors discuss the importance of the choice of wireless data representation that can have a big impact on the classification performance. The presented methodology was validated on two wireless signal identification research problems named modulation recognition and wireless interference identification. For each of the two research problems, three wireless signal representations were examined. Hence, six different CNNs were trained using massive and complex datasets. The results show the importance of choosing both the correct data representation and the machine learning approach.

The article in [31] discusses several applications of deep learning for the physical layer. Most importantly, the authors interpret a communication system as an autoencoder and introduce an end-to-end reconstruction optimization task that targets to jointly optimize the transmitter and the receiver side in a single process. Next, they extend the idea to multiple transmitters and receivers and describe the concept of radio transformer networks (RTNs) on raw I/Q samples for modulation classifications. The article concludes by discussing the open research challenges in the domain of deep learning and machine learning for wireless communications.

In [32], the authors inspired by supervised learning present two novel blind data symbol detection techniques for Multiple-Input Multiple-Output (MIMO) systems with low-resolution Analog-to-Digital converters (ADCs). In contrast to traditional MIMO detection techniques that require explicit channel state information at a receiver (CSIR), the proposed techniques learn a nonlinear function that characterizes the input-output relation of the system together with the effects of the channel matrix and the quantization at the ADCs. The authors also provide an analytical expression for the symbol-vector-error probability of the MIMO systems with one-bit ADCs when employing the proposed framework. Simulation results show that the proposed approach improves the symbol-error-rates (SERs) and is effective to use with ADCs with arbitrary number of precision levels.

The authors in [33] propose a method for interference identification between different wireless technologies in $2.4GHz$ industrial, scientific and medical (ISM) bands using CNN trained on frequency domain. The proposed CNN can identify transmissions of IEEE 802.11 b/g, IEEE 802.15.4 and IEEE 802.15.1 with overlapping frequency channels. The trained CNN can distinguish between 15 classes that represent the allocated frequency channel and the wireless technology. The experimentation results show that the proposed CNN outperforms proposed classifiers and can achieve a high classification accuracy that is greater than 95% for SNR values of at least $-5dB$.

7.2.3 Enhancing the coexistence of LTE and Wi-Fi by using CNN

As it has been mentioned in Section 7.1, in our previous work we have proposed an adaptive LTE scheme named mLTE-U that can enable fair coexistence between LTE and Wi-Fi in a flexible way [10]. mLTE-U can offer balanced spectrum access even when Wi-Fi does not support or use frame aggregation. mLTE-U builds on elements of LTE LAA. Hence, the evolved NodeB (eNB) uses an anchor channel in licensed band together with a secondary channel in unlicensed spectrum wherein it can transmit Downlink (DL) traffic. After the eNB estimates the channel in unlicensed spectrum as idle, it transmits for a variable TXOP followed by an adaptable muting period. This muting period can be exploited by other co-located networks, such as Wi-Fi to gain access to the medium. It becomes clear that the performance of the provided coexistence depends on the selection of TXOP and muting period duration. In [12], we further extended this work by introducing a Q-learning technique that enables autonomous selection of the optimal TXOP and muting period. In order to do so, the Q-learning scheme learns the TXOP and muting period combinations that allow LTE to achieve a targeted fair throughput.

In [10] and in [12], we assumed that the information of the wireless environment is known. This article goes a step further and with the assistance of deep learning and more specifically using CCN, it attempts to identify the type of the co-located networks. The CNN is trained and validated using COTS hardware for both the LTE and Wi-Fi networks. The learned information can be exploited by mLTE-U in order to select the appropriate TXOP and muting period.

7.3 CNN in a nutshell

During the last years, CNNs have been widely used by applications to perform image recognition and image classification. A CNN takes as input an image, it processes and classifies it into certain categories (e.g. dog, cat, horse, etc.).

In computer language, an image is translated as an array of pixel values. The dimensions of the array depend on the resolution of the image. For instance an array of $1920x1080x3$ corresponds to an image with *Width* of 1920 pixels and *Height* of 1080 pixels, while the *Depth* of 3 refers to the RGB values (the color of the pixel).

CNNs are inspired by biology and more specifically by neuroscience. When an eye looks at an object, individual neuronal cells are fired in the presence of curves and edges of specific orientation. Similarly to this, a computer identifies an object by investigating low level features (curves and edges) and by building up to more abstract concepts through consecutive convolution layers.

Figure 7.1 presents the typical structure of a CNN. As can be seen, the CNN

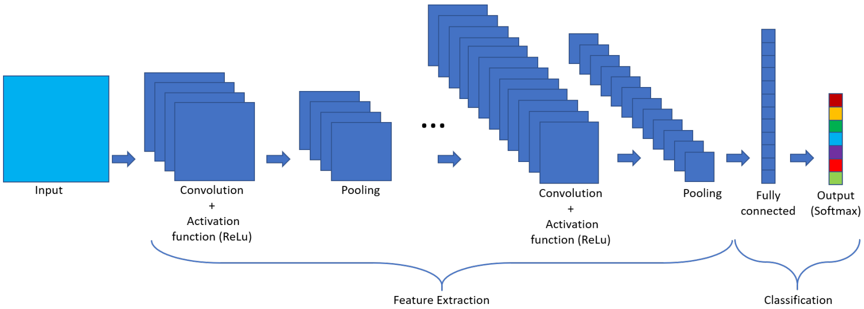


Figure 7.1: Structure of a CNN network. The input is processed by a series of convolutional layers, activated functions and pooling layers, ending up to a FC layer and a softmax classifier that gives the probability of the input belonging to each class.

takes an image as an input, it passes it through a series of hidden layers and gets an output that is the probability of the input belonging into a certain class. The hidden layers consist of a series of convolution, pooling and FC layers that aim to extract several abstract features.

Convolution layer is the first layer that is used to extract features from the input. This is being done by using a set of *filters* (also known as *kernels*) that perform a convolution over the input and are activated when a special feature is detected. These filters are small in terms of *Width* and *Height* compared to the original image but they extend through the full *Depth* of the input. During the convolution procedure, each filter is convolved across the *Width* and *Height* of its input and computes dot products between the values of the filter and the values of the input at every position. This procedure produces an *activation* or *feature map* that holds the responses of that filter at every position. The number of pixels that a filter shifts over the input matrix is given by the *stride*. For instance, when the *stride* equals to one, then the filter slides one pixel at a time, when the *stride* is two, then the filter slides two pixels at a time and so on and so forth. According to the filter size and the *stride*, it is possible that the filter does not fit totally in the input image. In that case the input is *padding* with zeros until the filter fits, or the part of the image where the filter does not fit is dropped. In the end, the output of every convolution layer is a set of *feature maps*, one for every filter that is convolved across the input of the layer. The filters of the first convolution layer detect low level features such as edges and curves of specific orientation. As we go deeper in the network, the output of a layer becomes the input of the next one. Hence, the consecutive convolution layers detect more complex and high level features. The convolution between a two-dimensional input x and a two-dimensional filter f can be computed as a discrete convolution and is expressed as:

$$\begin{aligned}(x * f)_{i,j} = x[i,j] * f[i,j] = \\ \sum_m \sum_n x[m,n] f[i-m][j-n]\end{aligned} \tag{7.1}$$

where m and n correspond to the *Height* and *Width* of the filter respectively. After the convolution, a *bias* term (b) is added.

The convolution layer is followed by a *rectifier activation function* that introduces non-linearity to the CNN. Typically, Rectified Linear Unit (ReLU) function is used that is defined as:

$$h(x) = max(0, x) \tag{7.2}$$

There are other common non-linear activation functions such as the hyperbolic tangent function (tanh) and the sigmoid activation function that are defined respectively as:

$$h(x) = \frac{2}{1 + e^{-2x}} - 1 \tag{7.3}$$

and

$$h(x) = \frac{1}{1 + e^{-x}} \tag{7.4}$$

For the k-th neuron the output Y_k will be:

$$Y_k = h((x * f)_{i,j} + b_k) \tag{7.5}$$

where $x * f$ is the convolution between the input and the filter, b_k is the shared value for the bias and h is the activation function.

A stack of few convolution and ReLU layers is followed by a pooling layer. The pooling layers are responsible to downsample the spatial dimensions of their input. The spatial pooling reduces the dimensions of each map but retains the important information. The most common type is a pooling layer that uses filters of size $2x2$ that are applied with a stride of 2, discarding this way the 75% of the activations, while the depth dimension remains unchanged. There are several types of spatial pooling such as *Max Pooling*, *Average Pooling* and *Sum Pooling*. Max Pooling selects the element with the highest value, the Average Pooling uses the average value of the elements and the Sum Pooling uses the summary value of the elements.

After a series of convolution, ReLU and pooling layers and towards the end of the CNN, we have the FC layer similar to a traditional neural network. The last feature map matrix is flattened into a vector and is fed into the *neurons* of the FC layer. These neurons have connections to all activations in the previous layer.

The last layer of the CNN is a *softmax classifier* that computes the probability of the input belonging to each class.

A common problem of the neural networks is overfitting, where after training, the weights of the network are very tuned to the training examples. As a result, the neural network does not perform well during the verification phase when new, untagged examples are used. In order to deal with this problem, *dropout* is used [34]. With this technique, a specific percentage of a random set of activations in a layer is set to zero. This way the network becomes more redundant and is able to give the right classification even if some of the activations are dropped out. This layer is used only during the training process and not during the verification process.

7.4 Equipment and experimentation setup

7.4.1 Networking equipment

For the purpose of this study, COTS LTE and Wi-Fi hardware equipment has been used in a fully controlled environment. The LTE network has been deployed and configured to operate in the unlicensed spectrum, next to a Wi-Fi network that is configured to operate in the same frequency channel. The experiments were performed at the LTE and Wi-Fi infrastructure of the W-iLab.t testbed of IMEC [14].

The radio part of the LTE network consists of software-defined radio (SDR) platforms and more specifically the Universal Software Radio Peripheral (USRPs) B210 boards [35]. This is a two-channel device that supports continuous radio frequency (RF) coverage that ranges from $70MHz$ up to $6GHz$. This allows us to configure the operational frequency in the unlicensed spectrum ($2.4GHz$ or $5GHz$). The USRP boards are connected to Gigabyte BRIX Compact PCs [36] that are used as host nodes, on which the LTE software runs. The LTE software that has been used is the srsLTE [37] open-source software suite. srsLTE is a highly modular LTE software framework developed by SRS and includes complete SDR LTE applications for the eNB, the UE and the Evolved Packet Core (EPC) side. The srsLTE framework is LTE Release 8 compliant with selected features of Release 9. Frequency Division Duplex (FDD) mode has been selected, similar to what is being used in LTE LAA. In order to operate LTE in unlicensed spectrum, the srsLTE software was configured to use the same center frequency as Wi-Fi channel 6 at $2.437GHz$ for the DL. The bandwidth has been set to $10MHz$ that is one of the most usable bandwidth configurations of LTE network deployments.

The Wi-Fi network consists of Zotac nodes [14] configured in infrastructure mode. One node operates as Access Point (AP) and it can have multiple associated stations. All the Wi-Fi nodes use a Qualcomm Atheros AR928X wireless network adapter together with the ath9k driver [38]. The Wi-Fi network has been set to operate in channel 6 of the $2.4GHz$ band, overlapping this way with LTE. Additionally, it has been configured to use the 802.11g mode.

Targeting a clean and controlled environment without any interference from other co-located networks, both the LTE and the Wi-Fi equipment were interconnected with each other using COAX cables through combiner and splitter units. Furthermore, remotely programmable attenuators have been used in order to control the power of each signal and create different coexistence scenarios (e.g. hidden terminal scenario). In order to train and verify the CNN network I/Q samples are collected from a USRP device that is interposed between the transmitting devices.

Figure 7.2 illustrates an indicative coexistence scenario of an LTE network consisting of one eNB and one UE operating next to a Wi-Fi network consisting of one AP and one station.

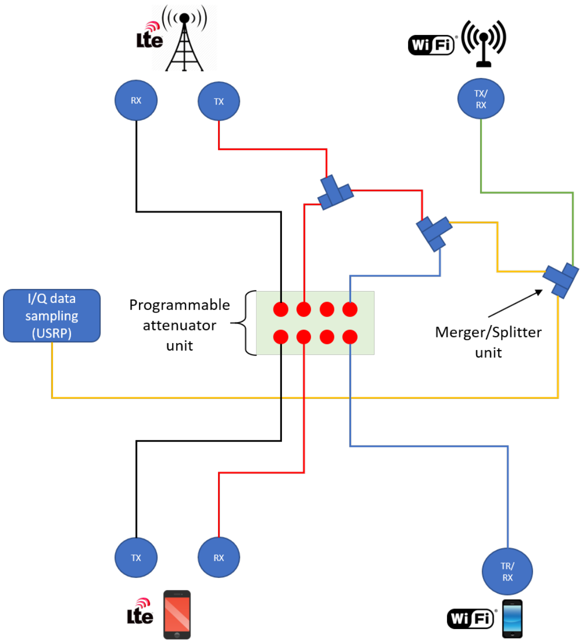


Figure 7.2: Indicative coexistence scenario between LTE and Wi-Fi. Each network consists of one end-devices connected to one base station.

7.4.2 CNN implementation details

The CNN network that have been used in this work has been trained and validated using the Keras software library [39]. Keras is a high-level API for neural networks written in Python. This API is able to run on top of several deep learning frameworks such as TensorFlow [40], Theano [41] and CNTK [42]. It is designed to run seamlessly on top of both Central Processing Unit (CPU) and Graphics Processing Unit (GPU). In our setup, we have used a NVIDIA GTX 1080 Ti GPU that incorporates 3584 NVIDIA Cuda cores.

In order to train and validate our CNN, $125,000$ examples, each one consisting of 4000 I/Q samples, have been collected over the air and have been labeled properly with the corresponding wireless technologies. The collected samples have been post-processed by including noise of different SNR values. This can be considered as a way of applying data augmentation techniques to I/Q samples. The SNR values range from $0dB$ to $+45dB$ with a step of $5dB$. As a result, the original data set size has been increased by a factor of 10. From the new data set, 70% randomly selected examples are used for training in batch sizes of 64. The rest 30% are used for validation of the model.

Additionally, the Adaptive moment estimation (Adam) optimizer [43] has been selected to estimate the parameters of the CNN. The learning rate of the algorithm has been chosen to be the default value $\alpha = 0.001$ in order to ensure convergence. The CNN has been trained for 200 epochs. However, an early stop of the training can be triggered when the accuracy of the network is not improved for 20 consecutive epochs.

In total, two CNNs have been trained. The one has been trained by using I/Q samples and the other by using their FFT representation in the frequency domain.

7.5 Experimental evaluation

7.5.1 CNN structure

The CNN structure that has been used in this study is illustrated in Figure 7.3. The input of the network, also known as the visible layer, has a size of $2x2000$ and it corresponds to either I/Q samples or the FFT of them. The I/Q samples are collected from a USRP device that is interposed between all the transmitted devices, as indicatively is shown in Figure 7.2.

The feature extraction part of the network consists of two hidden convolutional layers. These layers are used to extract high-level features from the input representation of the wireless signal. The first convolutional layer (convolutional layer-1) consists of 64 stacked filters, each one having dimensions $2x3$ that convolve with the input. As a result, 64 feature maps are created with dimensions $5x2002$. The second convolutional layer (convolutional layer-2) consists of 32 stacked filters of size $1x3$. These filters perform a convolution with the input of the layer, creating 32 feature maps with dimensions $6x1003$. For both convolutional layers, a zero padding of size 2 is applied to their input and a stride of 1 is used while convolving the filters.

Figure 7.3: Structure of the proposed CNN network.

Each convolutional layer is followed by a ReLu activation function. The distribution of the inputs for each layer can change during training, as the parameters of the previous layers change. To overcome this issue, a batch normalization [44] is applied after every ReLu function. Hence, the activations are properly adjusted and scaled, while the training rate increases. To reduce overfitting, each layer uses regularization with Dropout of 0.35 together with the L2 kernel regularizer. The L2 regularizer aims to penalize weights with large magnitudes. A pooling layer follows each convolutional layer, performing *Max Pooling*.

After the feature extraction part, the classification part follows and consists of two FC layers. First the input to the classification part is flattened and a FC layer is added (FC layer-1). This layer consists of 100 neurons. It uses a ReLu activation function, batch normalization, dropout of 0.5. and L2 kernel regularizer. The output of this layer is fed to a softmax classifier (FC layer-2) in order to estimate the probability of the input belonging to each class.

7.5.2 Classification accuracy

In order to evaluate the performance of the designed CNN that identifies the co-located LTE and Wi-Fi wireless technologies, it is necessary to compute the classification accuracy of the CNN. The classification accuracy corresponds to the fraction of predictions that the CNN identified correctly and it is defined as:

$$Class\_acc = \frac{N_{correct}}{Tot_{predictions}} \tag{7.6}$$

where $N_{correct}$ is the number of samples that have been classified correctly, while $Tot_{predictions}$ is the total number of predictions.

For the computation of the $N_{correct}$ and $Tot_{predictions}$, intermediate statistics of positive and negative predictions are required. These statistics correspond to:

- *True Positive (TP)* meaning that a wireless signal has been identified as belonging to a specific class and according to its label, it correctly belongs to that class.

- *True Negative (TN)* meaning that a wireless signal has not been identified as part of a specific class and according to its label, it does not belong to that class.

- *False Positive (FP)* meaning that a wireless signal has been identified as being part of a specific class, but according to its label, it does not belong to that class.

- *False Negative (FN)* meaning that a wireless signal has not been identified as belonging to a specific class, but according to its label, it does belong to that class.

Hence, function (7.6) can also be represented as:

$$Class\_acc = \frac{TP + TN}{TP + TN + FP + FN} \tag{7.7}$$

7.5.3 Experimentation results

The CNN network that is described in Section 7.5.1 has been trained for two different data representations. The first representation corresponds to the collected over-the-air I/Q samples, while the second corresponds to their transformation in frequency-domain through FFT. In the rest of the section, we refer to the trained CNN using I/Q samples as $CNN_{I/Q}$ and to the trained CNN using FFT as CNN_{FFT}.

The validation and training accuracy in relation to the number of epochs for both the I/Q and the FFT cases is presented in Figure 7.4. Additionally, Figure 7.5 presents the validation and training loss in relation to the number of epochs for both CNNs. The training and the validation of the networks have been done using the entire data set, including the different SNR values. As can be seen, both CNNs converge after approximately 40 epochs.

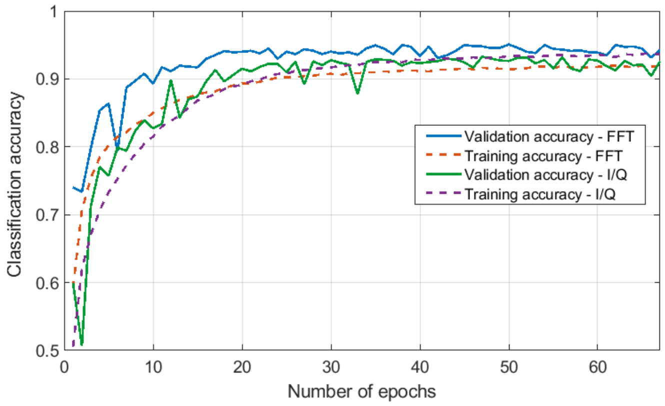


Figure 7.4: Validation and training accuracy in relation to the number of epochs for both I/Q and FFT data representations.

It can be observed that the validation accuracy of the CNN_{FFT} is slightly higher than its training accuracy. This means that the CNN_{FFT} has been trained on worse data than the ones that it identifies during the validation process. This may happen as the training data are randomly selected (70%) from the complete dataset. Additionally, the FFT representation has more information gaining features, as LTE and Wi-Fi have more distinguishable differences in the frequency

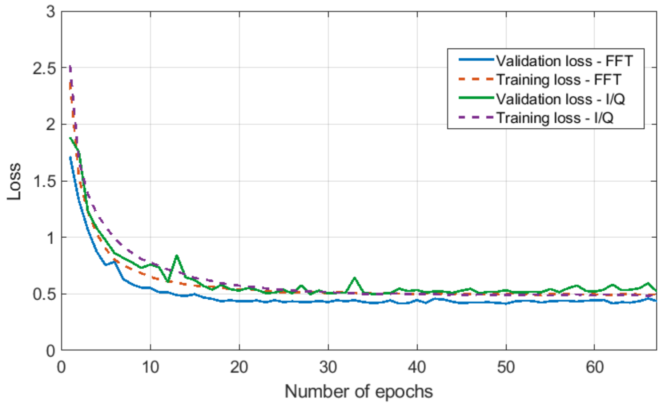


Figure 7.5: Validation and training loss in relation to the number of epochs for both I/Q and FFT data representations.

domain. As a result, the dropout has bigger impact on the FFT than on the I/Q representation. The validation accuracy of CNN_{FFT} is higher than the validation accuracy of the $CNN_{I/Q}$. The same results were noticed in [30] and [33] where the authors have used both I/Q and FFT data representations for interference identification through CNN. Respectively, the validation loss of the CNN_{FFT} is slightly lower than the validation loss of the $CNN_{I/Q}$. It can be concluded that the CNN that has been trained based on FFT data representation performs better than the CNN that has been trained using I/Q samples. Consequently, the LTE and Wi-Fi signals can be identified easier in frequency domain. This can be explained by the significant differences that the two wireless technologies have in this domain. According to the Orthogonal Frequency-Division Multiple Access (OFDMA) digital modulation scheme that is used by LTE, the LTE scheduler is able to schedule simultaneously multiple users in the frequency domain. On the other hand, Wi-Fi is a packet-based technology using Orthogonal Frequency Division Multiplexing (OFDM) digital modulation scheme. Hence, it allocates all the subcarriers to a single user.

Figure 7.6 presents the classification accuracy of both CNN in relation to the SNR. As can be seen, the CNN_{FFT} outperforms the $CNN_{I/Q}$ especially in low SNR values. More precisely, for $0dB$ of SNR, CNN_{FFT} offers an accuracy of approximately 80% compared to the accuracy of $CNN_{I/Q}$ that is 65%. For SNR values higher than $15dB$ the classification accuracy of both networks is similar. Especially for SNR values higher than $40dB$, the classification accuracy of $CNN_{I/Q}$ and CNN_{FFT} is very high and it approaches 98% and 99% respectively.

Figure 7.7 shows the confusion matrices for both CNNs with regard to different

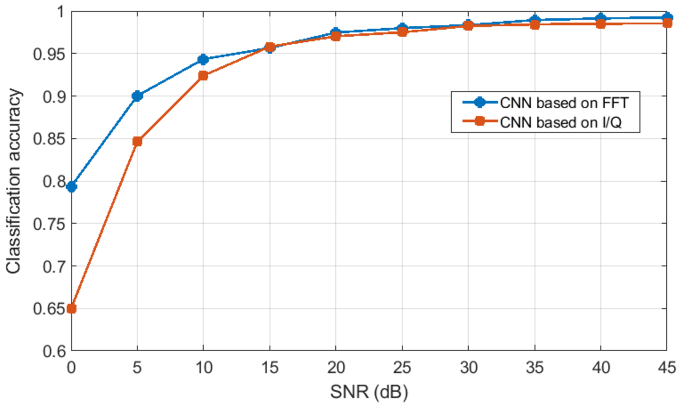
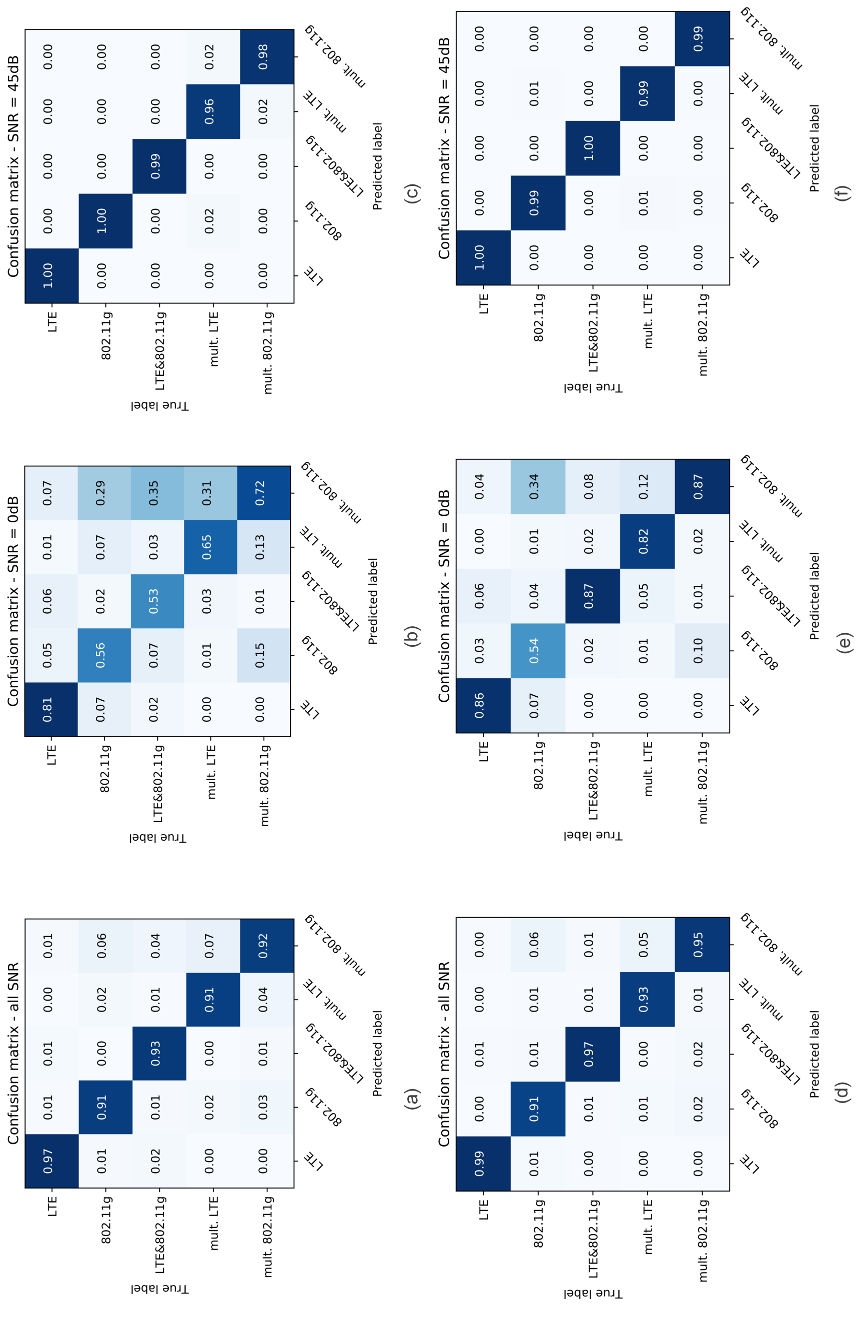


Figure 7.6: Classification accuracy for FFT and I/Q data representation in relation to SNR.

SNR scenarios. More specifically, Figure 7.7a and Figure 7.7d show the respective confusion matrices of $CNN_{I/Q}$ and CNN_{FFT} for all the SNR values. It can be observed that the CNN_{FFT} can identify the different transmitting networks slightly more accurate than the $CNN_{I/Q}$. Both CNNs identify less accurately single IEEE 802.11 and multiple LTE transmissions, while both of them achieve the highest classification accuracy by identifying single LTE transmissions.

Figure 7.7b and Figure 7.7e present the confusion matrices of $CNN_{I/Q}$ and CNN_{FFT} respectively for the lowest SNR value that corresponds to $0dB$. Here, it can be observed the superiority of FFT representation compared to I/Q. $CNN_{I/Q}$ classifies best single LTE transmissions, while it struggles to identify the other classes. More precisely, 35% of concurrent LTE and IEEE 802.11g transmissions, 31% of multiple LTE transmissions and 29% of IEEE 802.11g transmissions are identified as multiple IEEE 802.11g transmissions. On the contrary, CNN_{FFT} is much more accurate identifying best simultaneous LTE and IEEE 802.11g transmissions. Additionally, it lacks to identify 46% of single IEEE 802.11g transmissions that for 34%, they are identified as multiple IEEE 802.11g transmissions. Finally, Figure 7.7c and Figure 7.7f illustrate the corresponding confusion matrices for the highest SNR value of $45dB$. In this case, both networks are able to identify with excellent accuracy the different wireless transmissions. Again, the CNN_{FFT} is slightly better than the $CNN_{I/Q}$.

The experimentation results have shown that the performance of the CNN depends on the data representation that is used to train the network. Hence, it is important to investigate different data representations in order to have enhanced accuracy for a specific task. Furthermore, the classification accuracy can be improved by tuning the hyper-parameters of the CNN. The hyper-parameters are



Confusion matrix - all SNR

	LTE	802.11g	LTE&802.11g	mult. LTE	mult. 802.11g
LTE	0.97	0.01	0.01	0.00	0.01
802.11g	0.01	0.91	0.00	0.02	0.06
LTE&802.11g	0.02	0.01	0.93	0.01	0.04
mult. LTE	0.00	0.02	0.00	0.91	0.07
mult. 802.11g	0.00	0.03	0.01	0.04	0.92

(a)

Confusion matrix - SNR = 0dB

	LTE	802.11g	LTE&802.11g	mult. LTE	mult. 802.11g
LTE	0.81	0.05	0.06	0.01	0.07
802.11g	0.07	0.56	0.02	0.07	0.29
LTE&802.11g	0.02	0.07	0.53	0.03	0.35
mult. LTE	0.00	0.01	0.03	0.65	0.31
mult. 802.11g	0.00	0.15	0.01	0.13	0.72

(b)

Confusion matrix - SNR = 45dB

	LTE	802.11g	LTE&802.11g	mult. LTE	mult. 802.11g
LTE	1.00	0.00	0.00	0.00	0.00
802.11g	0.00	1.00	0.00	0.00	0.00
LTE&802.11g	0.00	0.00	0.99	0.00	0.00
mult. LTE	0.00	0.02	0.00	0.96	0.02
mult. 802.11g	0.00	0.00	0.00	0.02	0.98

(c)

Confusion matrix - all SNR

	LTE	802.11g	LTE&802.11g	mult. LTE	mult. 802.11g
LTE	0.99	0.00	0.01	0.00	0.00
802.11g	0.01	0.91	0.01	0.01	0.06
LTE&802.11g	0.00	0.01	0.97	0.01	0.01
mult. LTE	0.00	0.01	0.00	0.93	0.05
mult. 802.11g	0.00	0.02	0.02	0.01	0.95

(d)

Confusion matrix - SNR = 0dB

	LTE	802.11g	LTE&802.11g	mult. LTE	mult. 802.11g
LTE	0.86	0.03	0.06	0.00	0.04
802.11g	0.07	0.54	0.04	0.01	0.34
LTE&802.11g	0.00	0.02	0.87	0.02	0.08
mult. LTE	0.00	0.01	0.05	0.82	0.12
mult. 802.11g	0.00	0.10	0.01	0.02	0.87

(e)

Confusion matrix - SNR = 45dB

	LTE	802.11g	LTE&802.11g	mult. LTE	mult. 802.11g
LTE	1.00	0.00	0.00	0.00	0.00
802.11g	0.00	0.99	0.00	0.01	0.00
LTE&802.11g	0.00	0.00	1.00	0.00	0.00
mult. LTE	0.00	0.01	0.00	0.99	0.00
mult. 802.11g	0.00	0.00	0.00	0.00	0.99

(f)

Figure 7.7: Confusion matrices for both I/Q and FFT data representations and for different SNR values: a) $CNN_{I/Q}$ *for all SNR values, b)* $CNN_{I/Q}$ *for SNR of* $0dB$*, c)* $CNN_{I/Q}$ *for SNR of* $45dB$*, d)* CNN_{FFT} *for all SNR values, e)* CNN_{FFT} *for SNR of* $0dB$*, f)* CNN_{FFT} *for SNR of* $45dB$

the variables that define the structure of the network (e.g. number of convolutional layers) and variables that determine the training of the network (e.g. the learning rate). Finally, an advanced training that uses a rich dataset can further increase the performance of the CNN.

7.6 Enhancement of mLTE-U scheme with CNN

As we mentioned in Section 7.2.3, the designed CNN that has been trained to identify transmissions from co-located LTE and Wi-Fi networks, can be exploited by the proposed mLTE-U scheme in order to enhance the coexistence between the two wireless technologies. According to the mLTE-U scheme, LTE can transmit in the unlicensed spectrum for an adaptive TXOP that is followed by an adaptive muting period. During this muting period, other co-located networks (e.g. mLTE-U or Wi-Fi) can gain access to the wireless resources in order to transmit. Hence, every eNB that operates in unlicensed spectrum and deploys the mLTE-U scheme can use the trained CNN in order to identify the channel occupancy of each technology and adjust the mLTE-U parameters, aiming to enable fair coexistence.

Initially, when Wi-Fi transmissions are identified by the CCN, an eNB selects the TXOP and muting period configurations. Altruistically, the TXOP may be the shortest possible (e.g. $2ms$), while the muting period may be the longest possible (e.g. $20ms$). Subsequently, it should periodically monitor the potential LTE and Wi-Fi transmissions as reported by the CNN in order to adjust the mLTE-U parameters and to maintain a balanced access to the wireless resources for the two technologies.

Figure 7.8 demonstrates the exploitation of the CNN's output by mLTE-U in order to enhance the coexistence between LTE and Wi-Fi. The coexistence scenario is similar to the one illustrated in Figure 7.2, where one LTE network consisting of one eNB and one UE coexists with one Wi-Fi network consisting of one AP and one station. Both networks transmit only DL traffic in unlicensed spectrum and both networks aim to transmit as much as possible. The respective standalone DL throughput of LTE and Wi-Fi are $Thr^{mLTE-U}_{standalone} = 30.9Mbps$ and $Thr^{Wi-Fi}_{standalone} = 28.1Mbps$.

Wi-Fi is a packet-based technology that estimates the availability of the channel prior to every packet transmission. On the other hand, LTE is a scheduled technology that manages the assigned spectrum very efficiently. Hence, after it assesses the availability of the medium, it can transmit optimally during a TXOP. In our previous work [10], we saw that during the standalone operation, Wi-Fi occupies the channel for 70.10% of the time, meaning that Wi-Fi spends a high percentage of time sensing the medium. The corresponding LTE channel occupancy during a TXOP is optimal approaching 99.47%. In order to ensure fair access to the wireless resources when both networks are present, the mLTE-U eNB may

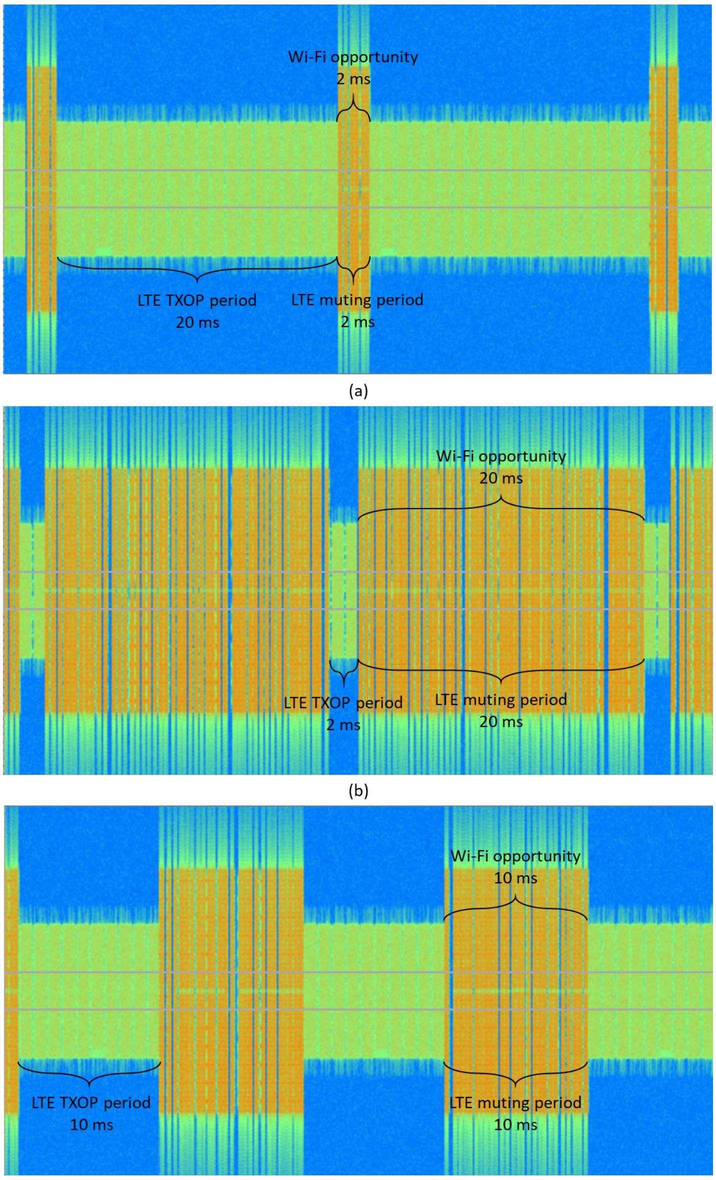


Figure 7.8: Enhancement of mLTE-U scheme with CNN. a) Spectrogram showing the unfair coexistence between LTE and Wi-Fi before the activation of the CNN. b) Spectrogram showing how LTE initializes the mLTE-U parameters after the trained CNN is activated. c) Spectrogram showing the fair coexistence between mLTE-U and Wi-Fi after the configuration of the mLTE-U scheme based on the CNN reports.

exploit the output of the CNN to ensure that the LTE channel occupancy is maintained close to 50%. If the eNB needs to increase the LTE channel occupancy, then it may increase the TXOP or decrease the muting period. Accordingly, if the eNB needs to give more opportunities to Wi-Fi, it may decrease the TXOP or increase the muting period. This decision can be made based on the traffic that the eNB needs to transmit. For instance, if the eNB transmits delay-sensitive traffic and the LTE occupancy time may be increased, then the eNB can use a shorter muting period in order to decrease the transmission delay. Additionally, LTE can give periodically longer channel opportunity to Wi-Fi. By using the output of the CNN, the new channel occupancy of Wi-Fi can be computed in order to estimate if Wi-Fi exploits the new channel opportunity or not. Further analysis of the way that the TXOP and muting period can be adjusted is not in the scope of this article and is considered as future work.

As shown in Figure 7.8a, before the activation of the CNN, mLTE-U is configured to use a long TXOP of $20ms$ that is followed by a short muting period of $2ms$. As result, LTE can achieve a high throughput corresponding to $Thr_{DL}^{mLTE-U} = 26.9Mbps$. In contrast, Wi-Fi can transmit only during the short muting period achieving a low throughput that corresponds to $Thr_{DL}^{Wi-Fi} = 1.88Mbps$.

After CNN is activated, it can identify the LTE and Wi-Fi transmissions in the unlicensed spectrum. Then, the eNB adjusts the mLTE-U parameters so that the shortest TXOP is used, followed by the longest muting period, as it is shown in Figure 7.8b. According to the CNN report, the eNB can estimate the channel use of each technology. Hence, it can compute that LTE transmits for approximately 9.1% of the time, while Wi-Fi transmissions occur during the rest 90.9% of the time. This channel access division among the two networks corresponds to $Thr_{DL}^{mLTE-U} = 2.18Mbps$ and $Thr_{DL}^{Wi-Fi} = 23.9Mbps$.

Afterwards, the eNB will attempt to adjust the mLTE-U parameters based on the reports of the CNN targeting to achieve fair coexistence of the two technologies. Eventually, this can be achieved by selecting a TXOP of $10ms$, followed by a muting period of $10ms$, as it is demonstrated in Figure 7.8c. In this case, LTE occupies the channel of approximately 50% of the time. In this case, the DL throughput of the mLTE-U network is $Thr_{DL}^{mLTE-U} = 15.4Mbps$ and the DL throughput of the Wi-Fi network is $Thr_{DL}^{Wi-Fi} = 14Mbps$.

It becomes clear that CNN can be exploited by the mLTE-U system in order to enhance the coexistence of LTE and Wi-Fi in unlicensed spectrum. However, as we discussed in [10], several other parameters can be obtained by the wireless environment and can be used to provide fair spectrum sharing. Such parameters can be the number of the active nodes in the unlicensed spectrum and the load of each node. As active, we consider the nodes that have traffic to transmit. By knowing this information, the mLTE-U scheme can be configured so that every active node in the unlicensed spectrum gets spectrum access opportunities proportional to the load of traffic that it needs to transmit, taking into account the provisioning of fairness within the limited spectrum. Obtaining information about the number of co-located active nodes, as well as the load of each network is a very interesting and complicated research topic that will be considered in our future work.

7.7 Conclusions and future work

Recently, the operation of LTE in unlicensed spectrum has been proposed as a method that can assist in dealing with the increasing wireless traffic. Towards a solution that can enable fair coexistence between LTE and other well-established wireless technologies in unlicensed spectrum, such as Wi-Fi, 3GPP announced the standard of LTE LAA. However, this mechanism may cause unbalanced coexistence between LTE and Wi-Fi when the latter does not support or use frame aggregation. In order to deal with this issue and enable fair coexistence, mLTE-U scheme has been proposed. In order to configure properly the mLTE-U scheme, information about the dynamically changing wireless environment is required. Among others, an essential and important information is the type of the co-located wireless technologies and their respective channel occupancy.

This article exploits the use of CNN in order to identify transmissions from co-located LTE and Wi-Fi technologies in unlicensed spectrum. The CNN is trained to identify LTE and Wi-Fi transmissions. Furthermore, the CNN can identify multiple LTE transmissions, multiple Wi-Fi transmissions and concurrent LTE and Wi-Fi transmissions that can be the result of hidden terminal effect. The designed CNN has been trained and validated using COTS LTE and Wi-Fi hardware equipment and for the following two wireless signals representations: I/Q samples and frequency domain representation through FFT. The classification accuracy of the trained CNNs is tested for different SNR values. The experimentation results have shown that the performance of the CNN is impacted by the data representation that is used to train the network. More specifically, we saw that the FFT representation offers higher classification accuracy compared to I/Q samples, especially for low SNR values. The obtained information can be used to compute the channel occupancy time of each wireless technology. Based on the channel occupancy time, the mLTE-U scheme can be configured properly in order to enhance the coexistence between co-located mLTE-U and Wi-Fi networks. For the purpose of this study and in order to train and verify the CNNs, COTS equipment has been used for both LTE and Wi-Fi network.

In the near future, several other parameters of the wireless environment, such as the active nodes and the load of traffic that each node needs to transmit will be investigated in order to enhance the fair coexistence in the unlicensed spectrum. Furthermore, this work can be extended by investigating the use of unsupervised learning for obtaining the necessary information. Unlike in supervised learning, labeled data input is not required. This makes unsupervised learning less complex to be implemented. As a result, the algorithm can act without human guidance making the proposed system fully autonomous.

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8

Conclusion

The only true wisdom is in knowing you know nothing.

– Socrates (470 BC - 399 BC)

Long Term Evolution (LTE) in unlicensed spectrum is expected to play a significant role in the upcoming 5G era. LTE is a wireless technology that can manage the wireless spectrum very efficiently, offering at the same time high data rates and low latency. However, the operation of LTE in unlicensed spectrum has posed several challenges to the research community, as it must harmoniously coexist with other well-established technologies in unlicensed spectrum (e.g Wi-Fi). Initially, LTE was designed to operate in licensed bands, assuming exclusive use of the assigned spectrum. Hence, there were no coexistence mechanisms that could render LTE a fair neighbor to other technologies in the unlicensed spectrum. As a result, techniques that can enable harmonized and equitable coexistence became a high level priority for the operation of LTE in unlicensed bands.

The research work in this dissertation has focused on studying the LTE operation in unlicensed spectrum and proposing solutions that can enable fair coexistence between LTE and Wi-Fi networks, as the latter is until today the most widespread wireless technology in unlicensed spectrum. This chapter summarizes the work has been done in this dissertation and presents future directions that can further assist in providing enhanced and fair coexistence.

8.1 Summary and conclusions

This dissertation aims to enable fair spectrum sharing between LTE and Wi-Fi in unlicensed spectrum in order to enhance the user experience of both networks. Initially, Chapter 2 provides the reader with the necessary background to understand the challenges that need to be overcome, in order to enable fair coexistence of LTE and Wi-Fi in unlicensed spectrum.

To enable such fair coexistence, it is very important to know the degree of the impact that LTE can have on Wi-Fi and what are the characteristics of each technology that can lead to unfair sharing of the wireless resources. Chapter 3 studies how the performance of Wi-Fi is affected by the presence of traditional LTE by using open-source software running on real hardware equipment. According to the results, LTE can have a severe impact on Wi-Fi in terms of throughput and latency. An important observation is that even if LTE does not have data to transmit, the performance of Wi-Fi is reduced seriously due to the numerous LTE control signals that are transmitted in specific Orthogonal Frequency-Division Multiplexing (OFDM) symbols in time and frequency domain within the LTE resource grid. We saw that the impact becomes higher when LTE transmits downlink (DL) or uplink (UL) data traffic. In order to study all the different levels of the impact that LTE may have on Wi-Fi, three different LTE transmit powers have been examined. For every LTE power level, the impact of both LTE control signaling and LTE data traffic on Wi-Fi has been studied. The results show that Wi-Fi suffers a tremendous performance degradation from the presence of LTE. It is concluded that the primary reason of the superiority of LTE over Wi-Fi is that it does not performs a clear channel assessment before a transmission. Hence, it either interferes with the ongoing Wi-Fi transmissions or it forces Wi-Fi to continuously backoff, leading it to starvation. This study makes clear that the implementation of coexistence and cooperation techniques is necessary to enable fair coexistence between the two technologies.

Chapter 4 described several cooperation techniques between co-located LTE and Wi-Fi networks. The proposed techniques are organized in two big categories. In the first category belong the techniques according to which, the networks cooperate directly by sending, receiving and interpreting in-band signal patterns. According to the second category, the networks can communicate indirectly between each other using a third-party entity (e.g. a Central Coordinator Entity (CCE)). The chapter analyzed the changes to the LTE and Wi-Fi protocols that are required by each technique, taking into account the regional regulators. Consequently, the open issues and the challenges have been discussed. We saw that the choice of the appropriate cooperation technique can be done based on several parameters, such as the required complexity and performance. For instance, a cooperation technique that allows the negotiation between LTE and Wi-Fi through a third-party entity can offer a high spectral efficiency at the cost of implementation complexity, as the addition of a CCE and the design of the communication protocol between the CCE and the cooperating technologies are required.

Towards a coexistence technique that can respect the regional regulations and can be applicable worldwide, The 3rd Generation Partnership Project (3GPP) announced the standard of LTE Licensed Assisted Access (LAA). However, the standard defines four priority classes that among other define the duration of the LTE transmission after the channel is estimated as idle. In Chapter 5, we saw that this predefined transmission duration can cause unfair coexistence between LTE and traditional Wi-Fi that does not support or use frame aggregation. In order to enhance the coexistence of LTE and Wi-Fi and enable fair spectrum sharing, we have proposed the muting LTE (mLTE-U) scheme. mLTE-U builds on elements of LTE LAA and as a result it deploys a secondary cell that operates in the unlicensed spectrum, next to the primary cell in the licensed spectrum. Additionally, an mLTE-U eNB has to perform a channel state estimation procedure before any transmission in unlicensed spectrum. After the channel state has been estimated as idle, the eNB can transmit for a adaptive TXOP, which is followed by an adaptive muting period. The muting period can be exploited by other co-located networks to gain access to the medium. The configurations of TXOP and muting period have an impact on the provided coexistence. Different scenarios of high interest have been examined to evaluate the coexistence between mLTE-U and Wi-Fi. The scenarios include various mLTE-U and Wi-Fi network densities, as well as static and moving end-devices. Simulation results showed that the appropriate configuration of mLTE-U can enable fair and harmonious coexistence in unlicensed spectrum. Finally, Chapter 5 discussed the procedure according to which optimal mLTE-U parameters can be autonomously selected in order to offer fair coexistence in a technology-agnostic way. The selection of the parameters can be done based on specific information that can be obtained by the wireless environment, such as the number of the co-located networks and the type of the traffic that must be served.

In Chapter 6, the proposed mLTE-U scheme was analytically studied. Firstly, the system model of mLTE-U, when it coexists with Wi-Fi has been analyzed and presented in detail. Next, a Q-learning technique has been designed for adjusting the parameters of mLTE-U. This technique can be used by an mLTE-U network to learn the wireless environment and autonomously select the optimal configurations (TXOP and muting period) that enable fair coexistence with other technologies. Simulation results showed how Q-learning learns the environment by trying to reach a specific target. This target refers to achieving a specific fair throughput according to the number of the co-located networks. Furthermore, the simulation results indicated how the Q-learning technique can be adapted to potential changes of the wireless environment (e.g. a new network is activated) and how it converges again to optimal policies. The proposed technique was compared with other conventional selection schemes, revealing the superiority of Q-learning over less complex mechanisms in providing fair coexistence with Wi-Fi.

The wireless environment by its nature is non-deterministic as it changes dynamically and continuously. The users of the networks change frequently, new networks may always be deployed and operating networks may always be abolished. Additionally, the amount of data each wireless node has to transmit and the according load on the network varies. It becomes clear that a technique that aims to provide fair coexistence to different wireless technologies in unlicensed spectrum must take into consideration potential changes to the wireless environment. Towards this direction, Chapter 7 exploited the use of CNN in order to identify co-located LTE and Wi-Fi technologies. The examined network has been trained to identify LTE transmissions and Wi-Fi transmissions. It can also identify hidden terminal effect that is caused by multiple LTE, multiple Wi-Fi or combined LTE and Wi-Fi transmissions. Within this chapter, COTS hardware equipment and open-source software have been used for the training and validation of the designed CNN. The designed CNN has been trained and validated for two wireless signal representations, namely In-phase and Quadrature (I/Q) samples and frequency domain representation through Fast Fourier Transform (FFT). The classification accuracy of the trained CNNs have been tested for various SNR values. The experimentation results showed that the CNN that has been trained using FFT data representation can achieve higher classification accuracy than the CNN that has been trained using I/Q data. The obtained information can be exploited by a coexistence mechanism (e.g. mLTE-U) to compute the channel occupancy of each technology. In the case of the mLTE-U scheme, the channel occupancy time can be used to select the TXOP and muting period configurations that enhance the coexistence between co-located mLTE-U and Wi-Fi networks. This has been verified within a proof of concept case-study using again COTS hardware equipment and open-source software, in which the mLTE-U scheme has been implemented.

8.2 Outlook

The operation of LTE in unlicensed bands was proposed for the first time in 2014 and until today a lot of progress has been made in research and standardization activities worldwide. Today, there are several variants of LTE operation in unlicensed bands such as LTE LAA, LTE-U and MulteFire. The first deployments of LTE LAA and LTE-U have already started. Among them, T-Mobile supports LTE operation in unlicensed spectrum in selected areas in the US (Brooklyn, Las Vegas, Bellevue, Richardson and Simi Valley) [1], while AIS supports it in some areas in Bangkok [2]. Regarding the end-devices, there is already a series of smartphones that support LAA and/or LTE-U by using several Qualcomm Snapdragon chipsets that incorporate the X12, X16, X20 and X24 LTE modems [3], or use the Exynos

9 Series 8895/9810 chipsets [4] [5].

By nature, the unlicensed spectrum is an unpredictable environment where several wireless technologies with different requirements and diverse channel access mechanisms compete with each other. In order to enable fair coexistence, it is very important to have a deep knowledge about the special characteristics of the technologies under investigation. We believe that a coexistence or a cooperation mechanism should take these characteristics into account when trying to achieve a balanced channel access among the different technologies. Otherwise, it is very likely that one technology will dominate the other, resulting in unfair use of the wireless resources.

Since the LTE operation in unlicensed spectrum was introduced, a lot of research effort has been focused on proposing, analysing and enhancing coexistence and cooperation techniques that can be applied between LTE and other well-established technologies in unlicensed spectrum, such as Wi-Fi. LTE in unlicensed spectrum is expected to play a significant role within the rising 5G era. This dissertation presented a series of cooperation and coexistence techniques that can enable fair spectrum sharing between LTE and Wi-Fi. We believe that it is very relevant to dedicate research efforts on techniques of this nature, as it is crucial to ensure that every technology that operates in a shared band respects other co-located technologies, as well as the regional regulations.

In this dissertation, a lot of focus has been put on providing fairness in unlicensed spectrum. Several works in the field approach fairness as equal channel access sharing between the different co-located wireless technologies. However, we have seen that such an approach does not offer always the desired fair coexistence. For instance, we can consider the case of one Wi-Fi network coexisting with one LTE network. The Wi-Fi network consists of one active end-user that transmits best-effort traffic, while the LTE network consists of ten users that play an online game. It is clear that by assigning 50% of the wireless resources to Wi-Fi and 50% to LTE will not result in fair coexistence. Towards a fair coexistence scheme, several wireless parameters must be taken into consideration. Such parameters can be the number and the type of the co-located networks, the number of active users and the volume of traffic that each user wants to transmit. Real fairness between the co-located wireless networks also has to consider the Quality of Service (QoS) demands of co-located devices and strive to maximize user-experience.

We strongly believe that the coexistence techniques should be able to adapt to the changes of the non-deterministic and dynamic wireless environment in order to provide the desired fairness. This way, the designed scheme can be robust against the changes to the unpredictable wireless environment in unlicensed spectrum bands. However, in order to adapt to the changes of the wireless environment, the coexistence scheme first should identify them. Machine learning, deep learning and neural networks can play a significant role in extracting information about the environment. Over the last years, the field of artificial intelligence has been evolved tremendously. Thus, there are several techniques that can be applied to the domain of the coexistence between different wireless technologies. By applying such techniques, valuable information can be extracted from the wireless environment such as the different co-located wireless technologies, the channel occupancy of each technology, the amount of traffic that is transmitted and more, without the need to decode other wireless technologies or the need to set up a collaboration channel between different technologies. Further research is required on how to obtain such information and how to use the extracted information to achieve harmonious coexistence. Today, the management of complex systems, such as the coexistence between diverse wireless networks, requires high domain expertise. Artificial intelligence could facilitate and simplify the management of such systems in a complementary way to the existing approaches. Additionally, artificial intelligence approaches can help to move away from centralized approaches and the associated complexity when dealing with large networks, to more distributed approaches that are more common in unlicensed bands and that can reduce the complexity to smaller and local problems.

Towards 5G, new approaches for spectrum sharing and new types of spectrum assignment arise and become more and more popular. Until today, spectrum management was performed in a quite conservative way and tended to be either licence exempt or assigned for long-term exclusive contract. A cellular operator could buy a 20 years license of spectrum, but would rarely use the entire allocation throughout the country. Towards a more flexible spectrum management, Citizens Broadband Radio Service (CBRS) scheme in US aims to dynamically allocate spectrum in the $3.5GHz$ band on demand to anyone (e.g a building owner) to operate Time Division Duplex (TDD) LTE. Similarly in Europe, the European Technical Standards Institute (ETSI) recently published the initial specifications for Licensed Shared Access (LSA). LSA is a further development of an industry proposal for Authorized Shared Access (ASA). ASA was introduced to enable access to additional frequency bands for mobile broadband, which were identified for IMT but not available in some countries. The concept was extended as Licensed Shared Access (LSA), with the potential for application to other services in addition to mobile broadband (e.g. wireless cameras). LSA focuses on operating TDD LTE on the $2300 - 2400MHz$ band, although extensions to other frequencies are not excluded. This spectrum is partially occupied for other purposes (telemetry, cordless cameras and defense applications) and is adjacent to the popular $2400MHz$ ISM band. It becomes clear that research is required to guarantee fair spectrum sharing and management between LTE and other technologies operating in these bands. Furthermore, research must focus on the way that the spectrum will be assigned to the new entrants in order to have minimal impact to the incumbent systems.

At the end of 2017, 3GPP successfully completed the initial 5G New Radio (NR) specifications that define the first phase of the global 5G standard. By the beginning of 2019, the first 5G NR networks and commercial devices are expected. 5G NR is a new air radio technology that enables the three following essential types of communication:

- enhanced Mobile Broadband (eMBB)
- massive Machine Type Communications (mMTC)
- Ultra Reliable Low Latency Communications (URLLC)

It is designed to improve the performance, the flexibility, the capability and the efficiency of the mobile networks. Initially, it is expected that 5G NR will be deployed in non-standalone mode, meaning that it will use the LTE core network (EPC). Additionally, according to the 5G NR dual connectivity feature, a mobile device is able to be connected simultaneously to both a NR and an LTE base station, leveraging benefits of both LTE and 5G connectivity. Later and according to the standalone mode, 5G NR will use the 5G core network that is being standardized by 3GPP. Additionally, it targets to get the most out of the available spectrum targeting licensed, shared and unlicensed deployments. Towards this direction, 3GPP has already kicked off a study item for 5G NR operation in unlicensed spectrum, both in licensed assisted access and standalone mode. It becomes clear that research needs to focus on techniques that guarantee the harmonious and fair co-existence between 5G NR and other wireless technologies such as LTE, Wi-Fi, etc. The spectrum utilization should be dynamic and optimal both horizontally (time domain) and vertically (frequency domain). This way, the different wireless technologies will serve their requirements and as a result the user-experience will be enhanced.

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