Spectrum Coexistence Mechanisms for Mobile Networks in Unlicensed Frequency Bands

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Abstract

Mobile network operators have historically experienced increasing traffic loads at a steady pace, which has always strained the available network capacity and claimed constantly for new methods to increase the network capacity. A key solution proposed to increase the available spectrum is the exploitation of the unlicensed spectrum in the 5 GHz bands, predominantly occupied by Wi-Fi technology. However, an uncontrolled deployment of mobile networks in unlicensed bands could potentially lead to a resource starvation problem for Wi-Fi networks and therefore degrade their performance significantly. To address this issue, the 3rd Generation Partnership Project (3GPP) standardised the Long Term Evolution Unlicensed (LTE-U) and Licensed Assisted Access (LAA) technologies. The main philosophy of these technologies is to allow mobile operators to benefit from the vast amount of available spectrum in unlicensed bands without degrading the performance of Wi-Fi networks, thus enabling a fair coexistence. However, the proposed coexistence mechanisms have been proven to provide very limited guarantees of fairness, if any at all. This thesis proposes several improvements to the 3GPP coexistence mechanisms to enable a truly fair coexistence between mobile and Wi-Fi networks in unlicensed bands. In particular, various methods are proposed to adjust the transmission duty cycle in LTE-U and to adapt/select both the waiting and transmission times for LAA. The main novelty of this work is that the proposed methods exploit the knowledge of the existing Wi-Fi activity statistics to tune the operating parameters of the coexistence protocol (duty cycle, contention window size and its adaptation, transmission opportunity times, etc.), optimise the fairness of spectrum coexistence and the performance of mobile networks. This research shows that, by means of a smart exploitation of the knowledge of the Wi-Fi activity statistics, it is possible to guarantee a truly fair coexistence between mobile and Wi-Fi systems in unlicensed bands. Compared to the 3GPP coexistence mechanisms, the proposed methods can attain a significantly better throughput performance for the mobile network while guaranteeing a fair coexistence with the Wi-Fi network. In some cases, the proposed methods are able not only to avoid degradation to the Wi-Fi network but even improve its performance (compared to a coexistence scenario between Wi-Fi networks only) as a result of the smart coexistence mechanisms proposed in this thesis. The proposed methods are evaluated for the 4G LTE standard but are similarly applicable to other more recent mobile technologies such as the Fifth Generation New Radio in Unlicensed bands (5G NR-U).

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List of Abbreviations

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	3^{rd} Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
5G NR-U	Fifth Generation New Radio in Unlicensed bands
ABS	Almost Blank Subframes
ACK	Acknowledgement
AI	Artificial Intelligence
AMPS	Advanced Mobile Phone System
AP	Access Point
BPSK	Binary Phase Shift Keying
BS	Base Station
CA	Carrier Aggregation
Cat 4 LBT	Category 4 Listen Before Talk
CCA	Clear Channel Assessment
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CHS	Channel Selection
CRS	Cell-specific Reference Signal
CSAT	Carrier Sensing Adaptive Transmission
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear-To-Send
CW	Contention Window
DC	Duty Cycle
DCF	Distributed Coordination Function
DCI	Data Centre Interconnect
DIFS	Distributed coordination function Interframe Space
DL	Downlink

DSA	Dynamic Spectrum Access
DynCW	Dynamic CW
DynCW-2	Dynamic CW with 2 adaptation points
DynCW-3	Dynamic CW with 3 adaptation points
eCCA	extended Clear Channel Assessment
ED	Energy Detection
EDGE	Enhanced Data rates for GSM Evolution
eLAA	enhanced LAA
eMBB	enhanced Mobile Broadband
eNB	evolved NodeB
ESC	Environmental Sensing Capability
ETSI	European Telecommunications Standards Institute
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FM	Frequency Modulation
FSK	Frequency Shift Keying
FTP	File Transfer Protocol
FWT	Fixed Waiting Time
GPRS	General Packet Radio Service
GSM	Global System for Mobile communications
GSMA	Global System for Mobile communications Association
HAP	Hyper Access Point
HARQ	Hybrid Automatic Repeat Request
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HSPA+	Evolved HSPA
iCCA	initial Clear Channel Assessment
IEEE	Institute of Electrical and Electronics Engineers
IMT-2000	International Mobile Telecommunications-2000
IoT	Internet of Things
IP	Internet Protocol
ISM	Industrial, Scientific and Medical
ITU-R	International Telecommunication Union Radiocommunication
LAN	Local Area Network
LBT	Listen Before Talk
LSA	Licensed Shared Access
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
LTE-eLAA	LTE-enhanced Licensed Assisted Access
LTE-LAA	LTE Licensed Assisted Access
LTE-U	Unlicensed LTE

LWA	LTE-WLAN Aggregation
MAC	Medium Access Control
MIB	Master Information Block
MIMO	Multiple Input Multiple Output
MMS	Multi-Media Message
mIoT	massive Internet of Things
mmWave	millimeter-Wave
NACK	Negative Acknowledgment
NFC	Near Field Communication
NMT	Nordic Mobile Telephone
NOMA	Non-Orthogonal Multiple Access
NSA	Non-Standalone
NTT	Nippon Telegraph and Telephone
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OMA	Orthogonal Multiple Access
OSDL	Opportunistic Supplemental Downlink
PCell	Primary Cell
PDU	Protocol Data Unit
PHY	Physical layer
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RAT	Radio Access Technology
RF	Radio Frequency
RFID	Radio Frequency Identification
RTS	Request-To-Send
SA	Standalone
SAS	Spectrum Access System
SCell	Secondary Cell
SDL	Supplemental Downlink
SIB1	System Information Block 1
SIFS	Short Interframe Space
SISO	Single Input Single Output
SMS	Short Message Service
SR	Spectrum Refarming
StatCW	Static CW
TACS	Total Access Communications System
TCP	Transmission Control Protocol
TD-CDMA	Time Division Code Division Multiple Access

TDD	Time Division Duplex
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TxOP	Transmission Opportunity
UDP	User Datagram Protocol
UE	User Equipment
UHF	Ultra High Frequency
UL	Uplink
UMTS	Universal Mobile Telecommunications Systems
URLLC	Ultra-Reliable and Low Latency Communications
UWB	Ultra Wide Band
VHF	Very High Frequency
VoIP	Voice over Internet Protocol
WCDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide interoperability for Microwave Access
WMAN	Wireless Metropolitan Area Network
WPAN	Wireless Personal Area Network

Chapter 1

Introduction

Communication can be broadly defined as the exchange of information and it is essential for individuals and businesses. Mobile communication is the communication with other people in different locations without any physical connection. Mobile networks are basically built and distributed over land areas known as cells providing the network coverage for different users to allow them to transmit different types of data. However, a set of frequencies is allocated for each cell to avoid interference between neighbouring cells providing high service quality. Numerous transceivers such as mobile phones, laptops and tablets can communicate together easily by joining these cells together over a wide area [1]. This means cellular networks allow further facilities that cannot be supported in other networks such as Local Area Networks (LANs). On the other hand, mobile devices allow people to access their business applications, email accounts, online buying and other services providing more flexibility to finish their works remotely [2].

1.1 Background

A dramatic growth over the last years has been recognised for the wireless communication services, since the First Generation (1G) cellular system which was introduced in the early 1980s. 1G was based on analogue Frequency Modulation (FM) allowing circuit switched voice services [2, 3]. Due to the high demand of cellular networks at that time, the Second Generation (2G) digital technology was introduced in the early 1990s based on Time Division Multiple Access (TDMA) or Code Division Multiple Access (CDMA) techniques providing circuit switched voice and packet switched data services [4]. A few enhancements were introduced during the 2G era such as General Packet Radio Service (GPRS) which is known as 2.5G and Enhanced Data rates for GSM Evolution (EDGE) which is known as 2.75G providing faster data rates. In 2000s, Third Generation (3G) cellular systems were introduced providing higher data rates and simultaneous speech and data services [5]. Voice over Internet Protocol (VoIP) and multimedia applications with broadband access are currently deployed within Fourth Generation (4G) cellular systems. Various techniques have been deployed in this generation such as multicarrier modulation and multiplexing techniques providing higher data rates [6, 7]. The new Fifth Generation (5G) cellular systems are currently under research and development to deliver rich services for users with superior data rates [8, 9] and introduce new service types requiring Ultra-Reliable and Low Latency Communications (URLLC) as well as machine-type communication within the Internet of Things (IoT). A brief description and some basic knowledge of evolution of cellular systems standards are provided in the following subsections. This brief clarifies the key differences between the various generations from 1G to 5G and how 5G technology is designed with extended capacity enabling next generation user experiences, supporting massive Internet of Things (mIoT) and delivering new services with superior data rates and low latencies.

1.1.1 Mobile Communication Systems and Standards

A. First Generation (1G) Cellular Systems

1G stands for the first generation of mobile phone technology. It was introduced in late 1970s and continued till the introduction of the 2G technology. 1G was based on analogue signals for telecommunication and was launched for the first commercial use in 1979 by Nippon Telegraph and Telephone (NTT) in Japan [2]. In 1980s, the first commercial standards for 1G had been introduced for various countries such as Nordic Mobile Telephone (NMT) in Nordic countries, Total Access Communications System (TACS) in the United Kingdom, Advanced Mobile Phone System (AMPS) in the United States, South America, Australia and China and C-Netz in Germany, Portugal and South Africa [10].

In this generation, devices were based on voice only, not including data or internet, services in the 800 MHz frequency band. The maximum speed that could be achieved by 1G networks was 2.4 Kbps. Moreover, the communication technology was based on Frequency Division Multiple Access (FDMA) technique coupled with Frequency Division Duplexing (FDD). The speech modulation was Frequency Modulation (FM) with Frequency Shift

Keying (FSK) for control signaling. In addition, the conversation was full duplex where both parties can communicate with each other simultaneously [10, 11]. Roaming was not supported in this generation, thus leading to call drops when move to another cell.

Despite of the simplicity of 1G networks, they had various drawbacks such as low capacity, low security, lack of internet services, large phone size, poor battery life and unreliable handoff.

B. Second Generation (2G) Cellular Systems

In order to provide more reliable and secure communications, the Second Generation (2G) technology was introduced using digital radio signals rather than analogue ones. The 2G technology, which is most significantly represented by the Global System for Mobile communication (GSM). It was widely deployed throughout the world in the 1990s. GSM was a circuit switched network that provided reliable voice services and limited data services. In particular, various fundamental services were offered in 2G that are still in use today such as Short Message Service (SMS), Multi-Media Message (MMS) and internet access [8, 12, 13].

The communication in 2G takes place using either TDMA or CDMA. In TDMA, a radio frequency is divided into time slots and then these time slots are allocated to multiple calls. On the other hand, in CDMA, a spread-spectrum technique is used where voice and data packets are separated using orthogonal codes and then transmitted using a wide frequency range, thus optimizing the use of available bandwidth [4, 13]. GSM which was mostly deployed in Europe is based on TDMA. Other 2G technologies deployed in US were typically based on CDMA instead.

A few advancements made during the 2G era where technologies such as 2.5G and 2.75G are addressed. The 2.5G technology introduced the General Packet Radio Service (GPRS) system which introduced the packet-switched data functionality in addition to voice and circuit-switched data that are used in GSM with a typical maximum data rate of 115 Kbps compared to the 9.6 Kbps data rate for circuit-switched data on GSM. The 2.75G technology introduced the Enhanced Data rates for GSM Evolution (EDGE) system which is considered as an Enhanced GPRS where new modulation and channel coding techniques were introduced in the radio interface with an increase in data rate to 384 Kbps. These two technologies were developed after 2G to achieve better data rates over 2G and helped in the transition into the subsequent 3G technology coming forwards [4, 14].

Moving from 1G toward 2G provided more security, better call quality, higher network capacity, smaller mobile phone devices, improved battery life, messaging services and internet browsing facilities. On the other hand, 2G technology suffers from a few drawbacks such as slow data rates and difficulty on handling complex and demanding data services such as video streaming or real-time applications.

C. Third Generation (3G) Cellular Systems

The Third Generation (3G) wireless technology was first introduced commercially in Japan in 2001 to provide a broad range of services with high data transfer rate and more data capacity. A wide variety of more advanced services were enabled such as multimedia services, web browsing, mobile internet access, fixed wireless internet access, video downloading, e-mails, TV through the internet, video calls, global roaming, online games and video conferencing [2, 15].

The support for media streaming services is the key distinction between 3G and 2G where the data are sent to the destination after partitioning it into small packets achieveing better voice quality and better connectivity due to a broader frequency bandwidth [3]. Various systems requirements were developed by the International Telecommunication Union Radiocommunication (ITU-R) to meet the International Mobile Telecommunications 2000 (IMT-2000) classifications. As a result, different types of cellular access technologies were deployed in the context of the 3G technology. In particular, CDMA and Time Division CDMA (TD-CDMA) were adopted as Universal Mobile Telecommunications Systems (UMTS) by the European Telecommunications Standards Institute (ETSI). UMTS is considered one of the earliest cellular systems that have been qualified by IMT-2000 [2, 15].

Within the 3G technology era, various specifications were addressed within the 3rd Generation Partnership Project (3GPP). CDMA 2000 and High Speed Packet Access (HSPA) approaches for Radio Access Network (RAN) were suggested to develop the 3G technology. HSPA provided data rates of up to 337 Mbps in the downlink and 34 Mbps in the uplink [3, 16, 17].

The 3.5G technology was designed to achieve an improvement in the performance over 3G technology in terms of data rate. It was designed based on Wideband CDMA (WCDMA) with higher data rates compared to 3G technology. Moreover, another evolution of HSPA was Evolved HSPA (HSPA+) which is sometimes considered as a 3.75G technology and it is considered the fastest 3G protocol [17, 18]. New functions were added by this technology such as higher order modulation and Multiple Input Multiple Output (MIMO) technique. Moreover, it supports Carrier Aggregation (CA) for higher peak data rates. In general, the 3G technology introduced various features and facilities with faster data rates and increased capacity. On the other hand, enabling these key features were costly to upgrade the 3G devices and to allocate a licensed spectrum accompanied with high power consumption.

D. Fourth Generation (4G) Cellular Systems

The Fourth Generation (4G) technology, which was first commercially deployed in Norway and Sweden in 2009, was introduced as an extension for the 3G technology with wider area coverage, more bandwidth and higher throughput. 4G systems are designed as packet switched systems with the help of Orthogonal Frequency Division Multiplexing (OFDM), MIMO and Ultra Wide Band (UWB) technology [19]. The key motivation of this technology is the increasing demand of mobile data services with high quality of service and high capacity.

4G systems are Internet Protocol (IP) based communication systems. In specific, a video streaming is over end to end IP. Quick and smooth handoff is one of the key new features of this generation. Gaming services, IP telephony, UWB internet access, high definition video conferencing and streamed multimedia are the main facilities that are offered by 4G [20].

Worldwide interoperability for Microwave Access (WiMAX) and Long Term Evolution (LTE) are the two competing standards of 4G. However, these wireless technologies can provide 4G service levels using some key technologies such as OFDM and MIMO [21, 22]. WiMAX was developed by the Institute of Electrical and Electronics Engineers (IEEE) as a part of the IEEE 802.16 standards. On the other hand, LTE was developed and released by the 3GPP in 2008. It uses radio waves instead of microwaves for data transmission. Moreover, it supports a peak data rate of 100 Mbps for high mobility and 1 Gbps for low mobility communications in downlink. LTE is optimized for low mobility up to 15 Km/h but it supports speeds up to 350 Km/h [24].

Both WiMAX and LTE are ITU approved technologies and they have some similarities where they both use OFDM and MIMO technologies, are IP based and compatible with CDMA and GSM networks. WiMAX is based on IEEE standards while LTE is a 3GPP standard [25]. Some companies switched from WiMAX to LTE due to its various advan-

Table 1.1: LTE versus LTE-A [10].

Functionality/Metric	**LTE**	**LTE-A**
Carrier spacing	1.4, 3, 5, 10, 15, 20 MHz	Forward: up to 100 MHz Reverse: up to 40 MHz
Modulation	Forward: QPSK, 16QAM, 64QAM Reverse: QPSK, 16QAM, 64QAM	Forward: QPSK, 16QAM, 64QAM, 256QAM Reverse: QPSK, 16QAM, 64QAM
MIMO	Forward: 2x2, 4x2, 4x4 Reverse: 1x2, 1x4	Forward: up to 8x8 Reverse: up to 4x4
Peak data rate	Forward: 150 Mbps (2x2 MIMO, 20 MHz), 300 Mbps (4x4 MIMO, 20 MHz) Reverse: 75 Mbps (20 MHz)	Forward: 3 Gpbs (8x8 MIMO, 100 MHz) Reverse: 500 Mbps (4x4 MIMO, 40 MHz)

tages and because it was developed by 3GPP which developed GSM and UMTS standards as well [22].

On the other hand, LTE Advanced (LTE-A) was standardised by the 3GPP Release 10 in 2011 adding more capabilities to the basic LTE standard enabling more facilities with much higher data rates and better performance. The study phase for this technology started in the 3GPP Release 9 [20]. This version of LTE improves the performance of LTE networks by using some new functionalities such as Carrier Aggregation (CA) up to 100 MHz in downlink, MIMO technology up to 8x8 in downlink, heterogeneous networks including macro, pico and femto cells and relay nodes [19]. This allows LTE-A to deliver maximum peak downlink data rates above 1 Gbps. Thus, LTE-A (i.e., Release 10) offers much faster data rates compared to the basic LTE (i.e., Release 8) for both downlink and uplink and provides enhanced network capacity. A comparison between LTE and LTE-A is provided in Table 1.1.

E. Fifth Generation (5G) Cellular Systems

The Fifth Generation (5G) technology is not only a new generation for mobile and wireless networks but also a key solution for societies, industries and individuals to enhance their digital ambitious by delivering rich services for consumers. This technology allows high connectivity to billions of devices and enables communication using the Internet of

Table 1.2: IMT-2020 5G requirements [28].

Requirement		Value
Data rate	Peak	UL: 10 Gbps DL: 20 Gbps
	User experience	UL: 50 Mbps DL: 100 Mbps
Latency	User plane	1-4 ms
	Control plane	20 ms
Spectral efficiency	Peak	UL: 15 bps/Hz DL: 30 bps/Hz
	5% of users	UL: 0.045-0.21 bps/Hz DL: 0.12-0.3 bps/Hz
	Average	UL: 1.6-6.75 bps/Hz DL: 3.3-9 bps/Hz
Mobility		0-500 Km/h
Bandwidth		100 MHz

Things (IoT) capability [26]. In general, this technology targets to build a new platform for Artificial Intelligence (AI) enhancing the existing services and providing new services with higher data rates, lower latency, lower cost, massive connectivity and higher system capacity. These services will be delivered by coexisting 5G networks with the previous generations of cellular networks achieving high data rates and secure connectivity. Thus, 5G will provide all the services that 4G can provide with an enhanced experience with speeds of up to 1 Gbps and latency of less than 4 ms. Moreover, licensed and unlicensed spectrum bands will be exploited with some innovative technologies in the 5G networks to deliver these superior services [27].

Various design goals are proposed within 5G technology across various countries to shape it. Thus, ITU-R defined the design goals for 5G under title IMT-2020 requirements which is shown in Table 1.2.

5G will achieve a superior experience compared to 4G where it will provide 10 to 100 times faster data rates with 10 times reduction in latencies. This superior experience will be achieved by using more spectrum bandwidth and the use of more spectrally efficient [29].

The 3GPP allowed officially various operators to launch their commercial 5G networks in Non-Standalone (NSA) version in 2017. On the other hand, the Standalone (SA) version of 5G was approved by the 3GPP in Release 15 in 2018. As a result, different countries such as United States and South Korea launched some 5G services in 2018 with limited coverage and limited services [26,30]. On the other hand, a few operators launched the 5G services on smartphones as the world's first 5G commercial networks in 2019.

Three frequency bands have been defined to support the 5G services; sub-1 GHz, 1 GHz to 6 GHz and above 24 GHz. The sub-1 GHz band supports some 5G services such as wide area IoT while 1 GHz to 6 GHz band is expected to be the primary band for 5G services deployment. On the other hand, above 24 GHz band is considered for short ranges with high capacity communication for ultra-high speed of 5G services [31]. However, different unlicensed spectrum in the 2.4 GHz and 5 GHz bands are considered within 4G and 5G technologies by various mobile operators providing connectivity for a huge number of IoT devices. In particular, various advancements have been performed for various technologies such as Wi-Fi, Unlicensed LTE (LTE-U), LTE Licensed Assisted Access (LTE-LAA) and MulteFire allowing 4G and 5G technologies to utilise these unlicensed spectrum bands.

F. An Overview of the Evolution of Cellular Systems

The aim of wireless communication is to deliver reliable communication with high quality of service. Each generation of wireless communication represents a key step to achieve this aim as illustrated in Fig. 1.1. However, each generation of mobile communication systems has appeared approximately every decade and each generation refers to specific standards established for mobile networks [2,32]. Moreover, each generation has requirements, which need to be met, that indicate several performance metrics of mobile networks such as data rate, latency, etc. More secure, reliable and faster communications have been provided by each generation from 1G to 4G technologies [33, 34]. On the other hand, the next generation of mobile networks (i.e., 5G technology) introduces new standards to support the increasing demand for mobile data traffic. In particular, this new generation aims to define a paradigm change for a user and application centric technology framework supporting the three use case families which include enhanced Mobile Broadband (eMBB), massive Internet of Things (mIoT) and Ultra-Reliable and Low Latency Communications (URLLC) [8]. eMBB focuses on user data rate and system capacity support, while mIoT focuses on the cost efficiency to connect billions of devices without overloading the mobile network. On the other hand, URLLC defines new requirements for industries such as remote surgery, cloud roboting and autonomous driving. Goals for 5G technology include massive capacity,

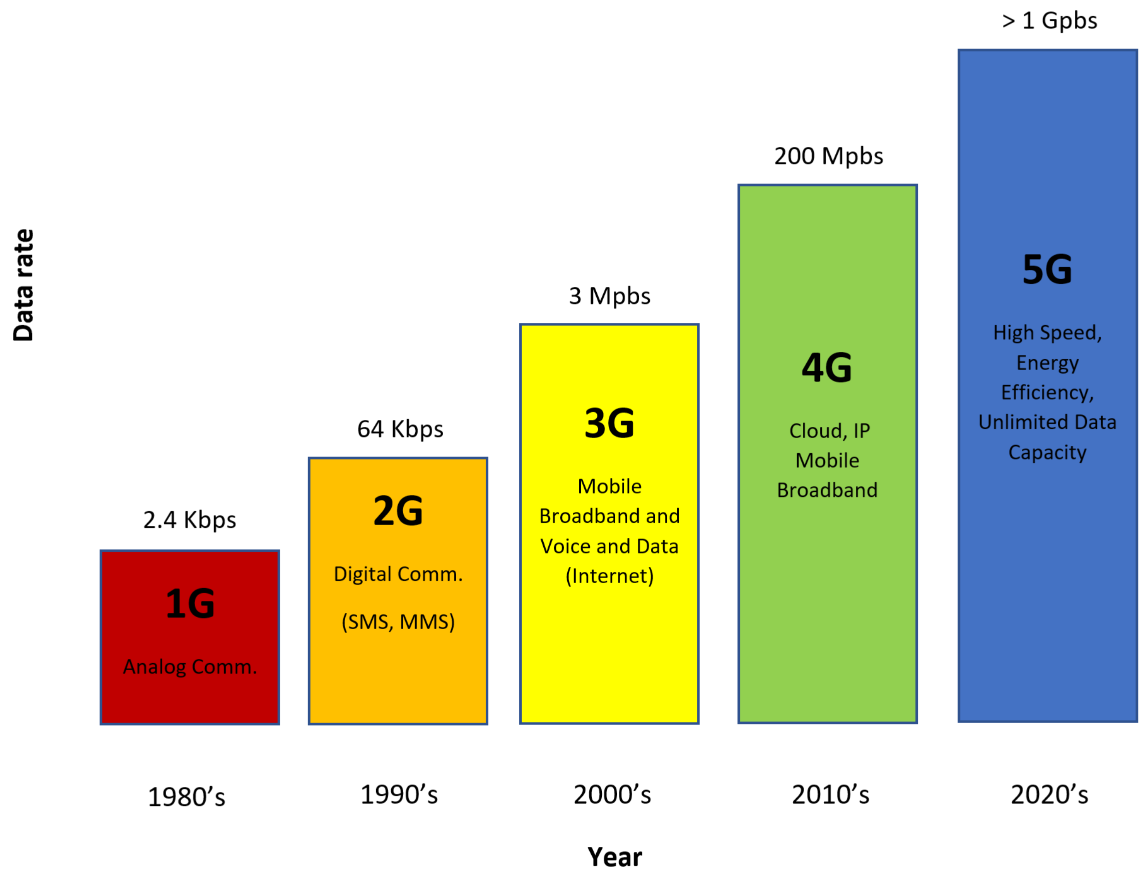


Figure 1.1: Evolution of cellular systems.

faster speeds with low power requirements to support a huge number of IoT devices [32,35].

Overall, it can be noticed that a lot of advancements have appeared in the area of mobile communication over the years. The key difference between the various generations from 1G to 4G is the increased data rate for each new generation. On the other hand, 5G technology will be a gateway for IoT with higher speed, higher capacity, less latency and less interference compared to 4G. Moreover, it will enable key solutions for several societies with massive IoT connectivity and enhanced broadband services. However, the several aspects of 5G technology require more capacity for communication systems and this is one of the challenging problems that faces 5G. On the other hand, different pathways to increase the capacity of communication systems and to utilise the spectrum more efficiently are proposed and explained in detail in the next subsection.

1.1.2 Pathways to Increase Capacity in Mobile Communication Networks

The increasing demands for mobile broadband services, the dramatic growth in mobile data traffic and the advancement in cellular networks standards towards the 5G technology forced mobile operators to expand greatly the capacities of mobile wireless networks. On the other hand, the available spectrum is limited and is a challenging problem to satisfy these demands [36]. However, these demands are essential and can be met by three main methods to expand the capacities of mobile networks: increasing spectrum efficiency; increasing network density and increasing radio spectrum [37, 38]. These three strategies are discussed separately in the following subsections.

A. Approaches to Increase the Spectrum Efficiency

Spectrum efficiency of communication system refers to the data rate that can be transmitted over a certain bandwidth (i.e., bit/s/Hz). This describes the utilisation of a given frequency spectrum by the Physical (PHY) layer protocol. Moreover, it refers to the maximum bit rate of a communication channel divided by a given bandwidth [39]. One of the techniques that can be used to increase the spectrum efficiency is the use of massive MIMO. In particular, deploying more antennas at the base station (normally between 64 and 128) to focus narrow beams towards a user can provide higher spectrum efficiency where the current MIMO systems are unable to cope with huge data traffic such as IoT systems, virtual reality and machine to machine communication to deliver the required spectrum efficiency [40]. Moreover, for massive MIMO, the massive number of antennas is needed at the base station but not at the user. Thus, this technique is an attractive deployment for new wireless networks standards such as 5G and beyond [41].

One more technique that can be used to increase spectrum efficiency is by using higher order modulation schemes. Modulation is the process of transforming the information into a suitable form that can be transmitted over the channel. In particular, in digital modulation, information is transformed into bits and mapped into a carrier frequency and then can be transmitted over the channel. On the other hand, the choice of the digital modulation scheme plays a key role in the performance of a given communication system [42]. For example, for 4G standards, an adaptive modulation scheme is used based on the signal to noise ratio to choose the modulation scheme among Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK) and Quadrature Amplitude Modulation

(QAM) [43]. BPSK and QPSK signals are less affected by noisy channels compared with QAM signals which have rectangular constellations. On the other hand, QAM signals can transmit a higher number of bits per symbol than BPSK and QPSK signals. Thus, higher order modulation can transmit higher number of bits per symbol leading to a higher throughput and better spectrum efficiency [44].

Another promising radio access technique that has been recently developed to be deployed in mobile networks to increase the system capacity is Non-orthogonal Multiple Access (NOMA) and it is considered as one of the key technologies in 5G [45,46]. The previous standards of mobile networks deployed Orthogonal Multiple Access (OMA) schemes to mitigate multiple access interference by allocating the communication resources to different users orthogonally in either a certain time slot, frequency band or code [47]. In particular, FDMA for 1G, TDMA for 2G, CDMA for 3G and OFDMA for 4G. On the other hand, the number of active users is limited in such schemes due to the limited availability of orthogonal resources. In contrast to OMA, NOMA allows multiple users to be placed on the same radio resource by non-orthogonal resource allocation at the expense of some complexity in receivers. On the other hand, interference mitigation techniques are deployed in such systems in order to mitigate the interference caused by using the same radio resource from multiple users [48]. Overall, the NOMA scheme is proposed to improve the spectrum efficiency of systems where multiple user terminals located at different positions and have different propagation losses are assigned the same frequency resources [49]. In particular, different transmission powers are delivered by the base station for these user terminals where the closer receiver of user terminal can extract the desired signal by eliminating the signals of other user terminals with the help of interference cancelation.

B. Approaches to Increase the Network Density

The second strategy to increase the mobile network capacity is to increase the density of the cellular network by reducing the cell sizes. Increasing network density is considered one of the promising solutions to provide better cell coverage and to utilise the spectrum. Small cells deployment operating in licensed spectrum has recently attracted mobile operators to meet user Quality of Service (QoS) requirements with low cost and easy deployment [50].

Cells in wireless networks can be categorised based on the cell radii and the transmitted power levels as macrocells, microcells, picocells and femtocells. Table 1.3 provides the typical values of cell radii and the transmitted power levels for each type. However,

Table 1.3: Wireless cells types [51]

Cell Type	Cell Radius	Tx Power Range
Macro	$>$ 1 Km $\sim$ 2 Km	40 W
Micro	250 m $\sim$ 1 Km	5 W
Pico	100 m $\sim$ 300 m	250 mW $\sim$ $>$ 2 W
Femto	10 m $\sim$ 50 m	10 mW $\sim$ 200mW

the spectrum efficiency of mobile networks can be enhanced by deploying dense network concept [52]. In particular, shrinking the size of radio cells can enable better reuse of the available spectrum across the coverage areas and can reduce the users competing to access the channel leading to higher spectrum efficiency and improving the data rates. As shown in Table 1.3, picocells are small cellular base stations that typically cover a small area such as offices, train stations, stadiums, shopping malls, etc. This type of cells is used for indoor scenarios to extend the network capacity. On the other hand, femtocells are low power small base stations that are typically designed for homes or small businesses. This type of cells is mainly designed to extend the service or at the edge of the coverage area [53]. Moreover, picocells and femtocells can be an effective solution to deal with the growth in demand for indoor data traffic which is more than 70% of the overall mobile data traffic [54]. These two types of cells can support more users and higher data rates. Thus, using more dense network can lead to higher data rates and higher spectrum efficiency as well.

C. Approaches to Increase the Radio Spectrum

The licensed spectrum is limited but it can be increased and utilised efficiently in order to increase the system capacity by following various techniques such as digital dividend, Spectrum Refarming (SR), millimeter-Wave (mmWave) and Dynamic Spectrum Access (DSA). All these techniques are described in detail below.

Digital dividend is the amount of the available radio spectrum achieved by the transition from analogue terrestrial television broadcasting to the digital technology only. Switching from analogue TV to digital platforms allows a huge decrease in spectrum consumption by terrestrial broadcasting since digital TV broadcasting needs less spectrum [55]. In particular, numerous subchannels can be transmitted digitally with the same amount of spectrum used for one analogue TV channel where less guard bands are required for digital transmission compared to the analogue one. This achieves more spectrum that could be allocated for other wireless services such as advanced mobile services, broadcast mobile TV and commercial wireless broadband services [55, 56].

In general, digital dividend depends on the regional spectrum regulations to avoid any interference that may be caused on spectrum band borders between broadcasting and mobile services. On the other hand, various parameters play a key role in the released amount of the radio spectrum achieved by the digital dividend such as the frequency channel bandwidth, network configuration and type of digital modulation [57]. The selection of these various parameters indicates the size of the digital dividend which can be exploited for various wireless services. Moreover, the size of the digital dividend varies between countries based on the neighbour countries and the interference limit regulations. In addition, the Very High Frequency (VHF) and Ultra High Frequency (UHF) bands, which are allocated for broadcasting services, are used in many countries for other services such as radio astronomy and aeronautical radio navigation [55, 58]. Thus, the size of the digital dividend may be reduced to protect these services. Overall, it can be noticed that the digital dividend is one of the most spectrum re-allocating techniques where 26% of deployments have been deployed using digital dividend bands in 2016 and delivers new digital TV services.

Another technique that increases the amount of spectrum available to a network by allowing different generations of cellular networks to operate in the same radio spectrum is called Spectrum Refarming (SR), which received a lot of attention due to its capability to meet the increasing demand of mobile services with high data rate, high capacity and low latency [59]. Due to the scarcity and the cost of the licensed spectrum for mobile services, SR is considered as a promising technique to greatly improve the efficiency of cellular spectrum by increasing the capacity without any need to acquire new spectrum. Due to the increasing demand of mobile services, the mobile traffic will gradually evacuate to any new deployed cellular generation. Specifically, when a new generation of cellular networks is deployed such as LTE, the old generations such as GSM and CDMA experience low traffic load and so does their demand for spectrum resources [60]. On the other hand, mobile operators need to keep serving users with the services of the old generations for a significant period before moving out to the new cellular generation. During this transition period, it is expected to have lower traffic utilisation than the designed network capacity in the older generation network, and the spectrum originally allocated to the older network can be shared or reallocated to the newer generation network. As a result, mobile operators consider SR as a promising technique to solve this problem solving the spectrum shortage problem and providing cost effective services [59, 60].

In general, two types of SR are considered; overlay SR model and underlay SR model. In overlay spectrum sharing model, secondary users can access the unused spectrum of primary users in an opportunistic manner while all users (i.e., primary and secondary) can simultaneously transmit over the same band in underlay model [61]. For example, Orthogonal Frequency Division Multiple Access (OFDMA) can utilise the unutilised subbands of GSM system when LTE Downlink transmission refarms the GSM bands. Thus, the key idea of SR is to enable different generations of cellular networks to operate over the same radio spectrum. On the other hand, the interference levels of neighbouring cells should be at minimum levels while using this technique [62].

Due to the increased demand of wireless services and the need for more capacity to support 5G requirements, the spectrum beyond 6 GHz frequencies has recently attracted researchers as a key solution to cope with the increased usage of smartphones and the IoT [63]. Despite of the under-utilised large bandwidths at millimeter-Wave (mmWave) frequencies, they face different challenges such as high penetration loss and diminished diffraction. Moreover, massive number of antennas are required for mmWave spectrum and smaller cells are needed to overcome blocking and path loss [64]. Those high frequencies provide more bandwidth than the frequencies below 6 GHz which are already heavily used by a broad range of wireless communication services. Moreover, these high frequencies are more suitable for small cell deployments where the short wavelengths of mmWaves increase the frequency reuse potential. Thus, the frequency reusability and large bandwidths make mmWave bands suitable for the high capacities required by 5G technology [65]. However, 5G requirements are expected to operate up to 100 GHz which can be guaranteed to operate over the spectrum of mmWaves starting at 30 GHz and going up to 300 GHz. Two phases have been performed by ITU and 3GPP for 5G standards. In phase one, the commercial needs have been addressed for frequencies under 40 GHz. These frequencies are addressed as low band mmWave systems where large bandwidths can be achieved by using the Carrier Aggregation (CA) concept [66]. On the other hand, the performance indicators have been addressed for frequencies over 40 GHz without the use of CA. However, CA is a mechanism which has been defined by 3GPP to achieve higher data rates by aggregating multiple carriers providing wider bandwidth.

New developments in radio technology improve the capabilities of various devices accessing the spectrum. These developments create opportunities to exploit the licensed and unlicensed spectrum more efficiently and to improve the performance of communication systems. These benefits are achieved by using several techniques that manage radio resources which are called Dynamic Spectrum Access (DSA) techniques [67]. The deployment of such techniques include spectrum sharing, channel assignment, interference control and software implementation to change the operating parameters. Cognitive communication systems have attracted researchers and mobile operators in the recent years to enable the coexistence of primary and secondary users in the same spectrum [37]. DSA techniques allow the use of spectrum white holes leading to the support of opportunistic transmission without any need for extra spectrum bandwidth.

The GSM Association (GSMA) introduced Licensed Shared Access (LSA) and Spectrum Access System (SAS) concepts to allow the licensed spectrum for IMT to be utilised by more than one entity. In particular, these concepts would increase the use of the licensed radio spectrum by allowing secondary users to use the licensed spectrum when the primary users are not using the allocated frequency bands [68, 69]. LSA and SAS principles are considered key solutions for mobile operators to access the licensed spectrum for mobile broadband. There have been recently interest in Europe and the USA for 2.3 GHz and 3.5 GHz band, respectively. It is worth mentioning that LSA and SAS principles are applicable for bands that are partially used by non-mobile incumbent services and are identified for mobile broadband as well [68].

LSA technology enables 3GPP networks to operate on a shared basis on the licensed 2.3 GHz band (i.e., band 40) in Europe. This requests mobile network operators to vacate the LSA frequency band for a certain geographical area for a given time period for any incumbent user such as military stakeholders or video cameras requesting access. This operation is accompanied with the deployment of CA mechanisms for a suitable combination between own and LSA spectrum based on the 3GPP Release 12 [70]. On the other hand, it is worth mentioning that the incumbent (Tier 1) user has more priority than the licensee (Tier 2). The spectrum management in this technology is based on a centralised database called LSA Repository. Incumbents provide information for this repository. Based on the availability of LSA spectrum, the access is granted for the mobile system asked to vacate some bands through the LSA controller. It is worth noting that there is no sensing scheme in this approach [71].

On the other hand, the SAS technology is similar to the LSA technology but designed to allow 3GPP networks to operate on a shared basis on the licensed 3.5 GHz band (i.e., bands 42 and 43) in the USA. The key difference between SAS and LSA is the existence of Tier 3 class which does not exist in LSA [72]. In particular, the SAS licensed spectrum bands are partially available for Priority Access License (PAL) users which are known as Tier 2 users and if there is a residual part of spectrum then it will be used for General Authorised Access (GAA) users which are known as Tier 3 users. Tier 2 users can access licensed 10 MHz spectrum slots (up to 70 MHz) in parts of the entire band while Tier 3 users can access at least 80 MHz of the entire band [73]. Smart grids and rural broadband systems are considered as PALs while mobile systems are considered as GAAs in this framework. In SAS, the incumbents are mainly military services using networks that are deployed near the coastal areas. The system deployment of this technology lies in two phases: in phase 1, the spectrum access is managed outside the Exclusion/Protection zones; in phase 2, an Environmental Sensing Capability (ESC) component is used and the access decisions are taken for Tier 2 and Tier 3 users based on these sensing tasks to coordinate the transmission inside the protection zones [72, 74]. The LSA and SAS technologies can be considered as promising techniques in spectrum management to guarantee more broadband wireless bandwidth as required for 5G technology and beyond.

Unlicensed spectrum bands have recently attracted researchers and mobile operators as a key solution for the various challenges of the increasing growth of mobile services and the scarcity of the available licensed spectrum. However, LTE in unlicensed bands is considered as a part of the evolution track to 5G technology and beyond. Several mechanisms have been developed to modify LTE to coexist with other wireless technologies over unlicensed bands in a fair manner. These mechanisms include LTE Unlicensed (LTE-U), LTE Licensed Assisted Access (LTE-LAA), LTE-enhanced Licensed Assisted Access (LTE-eLAA), LTE-WLAN Aggregation (LWA) and MuLTEfire [75]. Similar approaches for 5G networks operating in unlicensed bands (5G NR-U) have been defined more recently as well.

LTE-U was the first version of LTE over unlicensed bands based on 3GPP Release 12. In this version of LTE, a dynamic channel selection scheme is deployed to not degrade the Wi-Fi performance by using an adaptive Duty Cycle (DC) scheme to achieve the fairness between LTE and Wi-Fi networks. Listen Before Talk (LBT) mechanism is not mandatory in this type of LTE. In LTE-LAA, which was proposed in 3GPP Release 13, dynamic channel selection is deployed for Supplemental Downlink (SDL) based on LBT mechanism to reduce the collisions and to achieve fairness between the coexisting networks (i.e., LTE and Wi-Fi) [76, 77]. On the other hand, in LTE-eLAA, the Uplink (UL) aggregation has been added in 3GPP Release 14 leading to higher data rates, more capacity and less complexity [78]. Moreover, LWA was also developed in 3GPP Release 13, which configures the network to utilise both networks (LTE and Wi-Fi) simultaneously in a complementary manner. Therefore, LTE signals do not compete with Wi-Fi signals in such configurations. More capacity and less costs for network deployment can be achieved by following LWA configuration [79]. MuLTEfire technology, which was developed by the MuLTEfire Alliance, operates entirely over unlicensed bands based on 3GPP Release 13 and 14 [80]. Overall, all these technologies guarantee increased coverage and increased capacity for mobile systems.

1.1.3 Industrial, Scientific and Medical (ISM) Frequency Bands

The Industrial, Scientific and Medical (ISM) bands are parts of radio spectrum allocated internationally for industrial, scientific and medical applications. Various devices and applications operate over these unlicensed bands such as short-range devices based on the IEEE 802.11 WLAN and IEEE 802.15 Wireless Personal Area Network (WPAN) technologies, such as cordless telephones, home surveillance/CCTV systems and wireless internet connections. In addition, these bands are free to use without a government license and vary based on the different regions [81]. Moreover, both licensed and unlicensed operations share allocations within these bands. On the other hand, various communication equipments or operators should bear interference generated by different applications operating over ISM bands. Thus, the interference limits should be respected when operating over these unlicensed bands [82].

Due to the rapid growth of mobile services and applications, many mobile service providers are moving to use ISM radio bands for mobile communications to overcome the licensed spectrum scarcity. In particular, the free ISM bands allow mobile operators to utilise these free of cost frequency bands for radio transmission and reception leading to a higher spectrum efficiency across the globe. Operating over 2.4 GHz and 5 GHz bands are considered the most viable communication technologies to minimise the cost of microwave radio links. The use of these unlicensed frequency bands allows mobile operators to deliver more services including voice, video and data applications in an efficient manner [83, 84].

The radio spectrum is managed globally by ITU which divided the world into three regions. Region 1 covers Europe, Africa, the Middle East and the former Soviet Union states. Region 2 contains Americas and some eastern Pacific Islands. Finally, Region 3 covers non former Soviet Union states and most of Oceania. ISM band frequencies may differ based on these ITU regions as shown in Table 1.4. Thus, telecommunications over these unlicensed bands are possible considering the interference from other Radio Frequency (RF) and microwave technologies.

Table 1.4: ISM bands

Frequency range	**Centre Frequency**	**Bandwidth**	**Region**
6.765 ∼ 6.795 MHz	6.78 MHz	30 KHz	Based on local approval
13.553 ∼ 13.567 MHz	13.56 MHz	14 KHz	Worldwide
26.957 ∼ 27.283 MHz	27.12 MHz	326 KHz	Worldwide
40.66 ∼ 40.7 MHz	40.68 MHz	40 KHz	Worldwide
433.05 ∼ 434.79 MHz	433.92 MHz	1.74 MHz	Region 1
902 ∼ 928 MHz	915 MHz	26 MHz	Region 2
2.4 ∼ 2.5 GHz	2.45 GHz	100 MHz	Worldwide
5.725 ∼ 5.875 GHz	5.8 GHz	150 MHz	Worldwide
24 ∼ 24.25 GHz	24.125 GHz	250 MHz	Worldwide
61 ∼ 61.5 GHz	61.25 GHz	500 MHz	Based on local approval
122 ∼ 123 GHz	122.5 GHz	1 GHz	Based on local approval
244 ∼ 246 GHz	245 GHz	2 GHz	Based on local approval

Many Radio Frequency Identification (RFID), Near Field Communication (NFC) and wireless payment systems use the 13.56 MHz ISM band. Moreover, the 915 MHz and 2.4 GHz bands are exploited for short range communications such as smart home applications using Zigbee technology. On the other hand, various telecommunications services operate over the ISM bands such as radar, Wi-Fi, Bluetooth and Zigbee [85]. In particular, the 2.4 GHz band is exploited for radar systems due to the availability and inexpensive cost of this frequency band. In addition, most Wi-Fi, Bluetooth and household technologies operate over the unlicensed 2.4 GHz band [86]. This results in overcrowding when multiple devices use the same unlicensed radio space. The 2.4 GHz and 5 GHz ISM bands are popular for WLANs [87]. The key differences between these two ISM bands are the coverage range and the bandwidth that are provided by these bands. In particular, the 2.4 GHz band transmits at lower data rates but provide wider range while less coverage and higher data rates are provided by the 5 GHz band. These features are due to the fact that higher frequencies (i.e., 5 GHz band) cannot penetrate easily through objects providing less coverage and higher data rates. Due to the lower congestion and more available channels, the 5 GHz band has recently attracted researchers and mobile operators more widely for Wi-Fi systems compared to the 2.4 GHz band [88, 89]. Therefore, the 5 GHz band is considered in this study since it is less crowded and there is currently a new trend of high new radio that uses some bands in the sub 6 GHz band. A comparison between the 2.4 GHz and 5 GHz bands is provided in Table 1.5.

Table 1.5: 2.4 GHz versus 5 GHz ISM bands

Feature	**2.4 GHz**	**5 GHz**
Bandwidth	83 MHz	725 MHz (FCC)
Channels	3 non-overlapping	23 non-overlapping (FCC)
Coverage	Longer	Shorter
Data rate	Lower	Higher
Interference	Higher	Lower
IEEE 802.11	b, g, n	a, n, ac

1.1.4 Wi-Fi Technology

Wi-Fi technology employs a Distributed Coordination Function (DCF) protocol which uses carrier sensing to maximise the throughput while preventing packet collisions. DCF is mainly based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) MAC protocol [90, 91]. In particular, if there is a Wi-Fi node that has data to transmit, it needs to sense the channel firstly to be idle for a DCF Interframe Space (DIFS) duration. If the channel is clear, it will transmit a Request-To-Send (RTS) to the destination node. Then, the destination will send a Clear-To-Send (CTS) if it is ready to receive data. The Wi-Fi node will transmit its data when the sender node receives the CTS message. In addition, the destination will send an Acknowledgment (ACK) to the sender node for the successful data reception after a Short Interframe Space (SIFS) time. On the other hand, if the channel is not clear, the node keeps monitoring the medium until it becomes idle for a DIFS time, then it picks a random backoff time and counts down (in particular, a random number of time slots which is within a CW that has lower and upper bounds as shown in Table 1.6). When the backoff timer reaches zero, the Wi-Fi node can perform the transmission for a maximum time determined by the Transmission Opportunity (TxOP) parameter as shown in Table 1.6. The process is illustrated in Fig. 1.2. It is worth noting that, given the Wi-Fi MAC protocol, Wi-Fi nodes may be unable to access the channel if it is heavily and selfishly used by other technologies in the same channel.

1.1.5 LTE and Wi-Fi Coexistence

With the evolution of wireless applications and services, the spectrum shortage has become a challenging problem. Unfortunately, the cost and the availability of the licensed spectrum is also a challenging problem [94]. Therefore, it is necessary to find a solution to have

Table 1.6: Access categories for IEEE 802.11n [92, Table 7-37] and IEEE 802.11ac [93, Table 8-105].

Access category	$\mathbf{CW_{min}}$	$\mathbf{CW_{max}}$	**TxOP**
Background	15	1023	1 frame
Best effort	15	1023	1 frame
Video	7	15	3.008/6.016 ms
Voice	3	7	1.504/3.264 ms

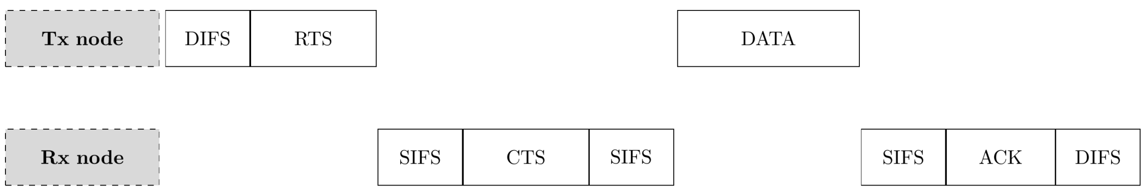


Figure 1.2: Wi-Fi MAC scheme [91].

more spectrum bands. One of these solutions is to utilise the unlicensed spectrum more efficiently by occupying these bands with other wireless technologies. The unlicensed bands are occupied by some wireless technologies such as Wi-Fi. These bands are attractive since they are free and there is more than 500 MHz of free spectrum for different services at the 5 GHz band [95].

Recently, the unlicensed spectrum has attracted mobile operators due to the large amount of accessible spectrum. On the other hand, this large spectrum is shared by other technologies such as Wi-Fi networks. Thus, it is important not to degrade the performance of this existing technology by designing a fair coexistence mechanism. LTE technology has been recently developed to operate in unlicensed bands to give higher throughput, better performance in dense deployment, and more capacity [96]. Despite this, the coexistence of LTE with Wi-Fi in these free bands creates many challenges since there is a main difference between the Medium Access Control (MAC) layers of LTE and Wi-Fi.

In Wi-Fi, the MAC layer is based on the CSMA/CA mechanism. Thus, the node senses the channel and if it is free then the transmission will take place, otherwise the node would select a random back-off timer and the transmission starts when the timer decreases to zero. While in LTE, there is no sensing scheme. As a result, the coexistence of LTE with

Table 1.7: LTE-U versus LTE-LAA.

Aspect	**LTE-U**	**LTE-LAA**
Regions	No need for LBT (USA, China & Korea)	LBT is required (Europe & Japan)
Fairness	Less fair	More fair
PHY/MAC modifications	Less modifications	More modifications
3GPP Release	10-12	13

Wi-Fi in the unlicensed bands can severely degrade the performance of Wi-Fi since the Wi-Fi node sends its own data after checking the availability of the channel. Therefore, when there is interference from an LTE network which does not use any sensing scheme, Wi-Fi node stays on listen mode without any transmission. This may cause Wi-Fi starvation while LTE exploits the unlicensed spectrum [97].

Obviously, the idea to coexist LTE with Wi-Fi in the unlicensed band is not to unseat the Wi-Fi technology, but to increase the spectral efficiency and the capacity of the mobile network without degrading the performance of the existing Wi-Fi network. LTE technology has a centralized architecture in which a base station schedules channel access in licensed bands [98]. In contrast, Wi-Fi technology has a decentralized channel access mechanism based on a CSMA protocol [99]. Therefore, there is a need to manage this channel access differences between LTE and Wi-Fi through a fair and friendly mechanism. The regulatory requirements such as the allowed transmit power should be taken into account while designing a fair coexistence mechanism in the unlicensed spectrum. In some regions, such as Europe, an LBT protocol for Clear Channel Assessment (CCA) while accessing the unlicensed channel is required. In other regions, such as USA, there is no need for LBT protocol [100]. The first version of LTE in the unlicensed band is called LTE-U which does not use Listen Before Talk (LBT) mechanism, while LTE-LAA and LTE-enhanced LAA (LTE-eLAA) are the most recent versions and include an LBT mechanism. The major differences between LTE-U and LTE-LAA are provided in Table 1.7.

Unlicensed spectrum has recently attracted the industry and researchers to be utilised for LTE deployments [101, 102]. Thus, LTE has been recently deployed to operate over unlicensed bands providing enhanced mobile network capacities [96,103]. The same concept is introduced as well in the 3GPP specification for 5G New Radio Unlicensed (5G NR-U) and therefore currently constitutes a research topic of recent interest [104, 105].

Different requirements need to be taken into account to design an unlicensed LTE such that it allows a fair coexistence with Wi-Fi over unlicensed bands [97,106–108]. 3GPP TR 36.889 describes the "fairness" between the coexisting networks (i.e., LTE and Wi-Fi) over the unlicensed 5 GHz band as the ability of an LTE network not to impact the existing network (i.e., Wi-Fi) active on the same carrier more than an additional Wi-Fi network in terms of throughput and latency [96].

Two main approaches have been proposed in the literature to achieve a fair coexistence between these heterogeneous technologies [96, 103]. In particular, for some markets, such as Europe and Japan, a LBT protocol for CCA is required for accessing unlicensed bands, while in other markets, such as USA and China, there is no need for such protocol. LTE-U, which does not need an LBT protocol, was the first version of LTE over unlicensed bands and was proposed by the industry consortium LTE-U Forum [100]. LTE-U was aimed at allowing a quick deployment of LTE networks in 5 GHz bands in those countries that do not require an LBT protocol by reusing mechanisms already available in the 3GPP standard. The three main mechanisms on which LTE-U relies are carrier selection, ON/OFF switching and CSAT to adapt the Duty Cycle (DC) of the transmissions [91,109]. However, LTE-U is unable to fully meet the requirement of fair coexistence as defined in 3GPP TR 36.889. As a result, the 3GPP in Release 13 proposed LTE-LAA for Supplemental Downlink (SDL) where an LBT protocol is required for transmission over unlicensed bands [96].

1.1.6 LTE in Unlicensed Spectrum (LTE-U)

LTE-U is the first version of LTE over the unlicensed band and it was developed by the industry consortium LTE-U Forum for countries such as USA and China where there is no need for Listen Before Talk (LBT) mechanism for the transmission over unlicensed spectrum. In these countries, the design of coexistence mechanisms does not need modifying Release 10/11 LTE PHY/MAC standards, which means no modifications for the LTE interface. In such mechanisms, intelligent software is used to deploy the LTE networks with the Wi-Fi networks over the unlicensed spectrum [100]. Thus, the industry consortium LTE-U Forum proposed this version of LTE (i.e., LTE-U) without LBT requirements. The adopted approach here is to exploit already existing features of the LTE standard to facilitate the coexistence with Wi-Fi networks.

Three mechanisms that were already included in the LTE standard can be used to deploy LTE as a good neighbour with Wi-Fi in the unlicensed spectrum without LBT as illustrated in Fig. 1.3. First, the Channel Selection (CHS) mechanism. Here, the LTE-U small cells monitor the spectrum to choose the best channel for the Supplemental Downlink (SDL) transmission. If a clean channel is identified, the Secondary Cell (SCell) can be operated without concerning of co-channel communications [110, 111]. However if there is no clean channel according to the received signal energy in each Wi-Fi channel, then the Carrier Sensing Adaptive Transmission (CSAT) algorithm is used [112]. The CHS is suitable where the density of traffic is low and clean (empty) channels are likely to be found.

In the CSAT algorithm, LTE-U can share the same channel with Wi-Fi or another LTE-U by using the concept of Time Division Multiplexing (TDM) coexistence based on medium sensing. In particular, the LTE small cells sense the channel for a duration longer than the sensing duration of Wi-Fi (for LBT and CSMA), then based on the observed activities, CSAT decides the duty cycle of the LTE transmission. Thus, LTE-U is periodically activated and deactivated by control elements of LTE MAC, and the Wi-Fi transmissions can take place during the OFF periods of LTE-U. The main idea of CSAT is to define the duty cycle for the transmission of LTE-U, where the SCell can transmit at a relatively high power during the CSAT ON periods, while in the CSAT OFF periods the SCell will gate off to avoid competing with Wi-Fi as illustrated in Fig. 1.4. During the LTE-U OFF times, the Wi-Fi transmissions will be monitored and then the LTE-U duty cycle will be adjusted accordingly to attempt to give a fair amount of transmission opportunities to the Wi-Fi network.

The third algorithm to deploy LTE with Wi-Fi in the unlicensed spectrum without LBT is the Opportunistic SDL (OSDL), where the secondary component in the unlicensed band can be turned off to avoid transmissions of overheads such as Cell-specific Reference Signals (CRSs) when the small cell is lightly loaded, which reduces the interference to the neighbouring Wi-Fi access points. This algorithm is suitable in areas where dense deployments, where no clean channel is available since it reduces the impact on co-channel communications [112].

The adjustment of the CSAT parameters such as the cyclic ON/OFF ratio and the transmission power depends on the measurements performed by the devices or small Base Stations (BSs). These parameters can be optimized to give better performance. In general, the coexistence between LTE-U and Wi-Fi without LBT functionality is called LTE-U duty-cycling, i.e. managing the transmission of LTE-U by adjusting the duration of the ON/OFF periods. The LTE-U duty-cycling has some advantages such as not requiring significant

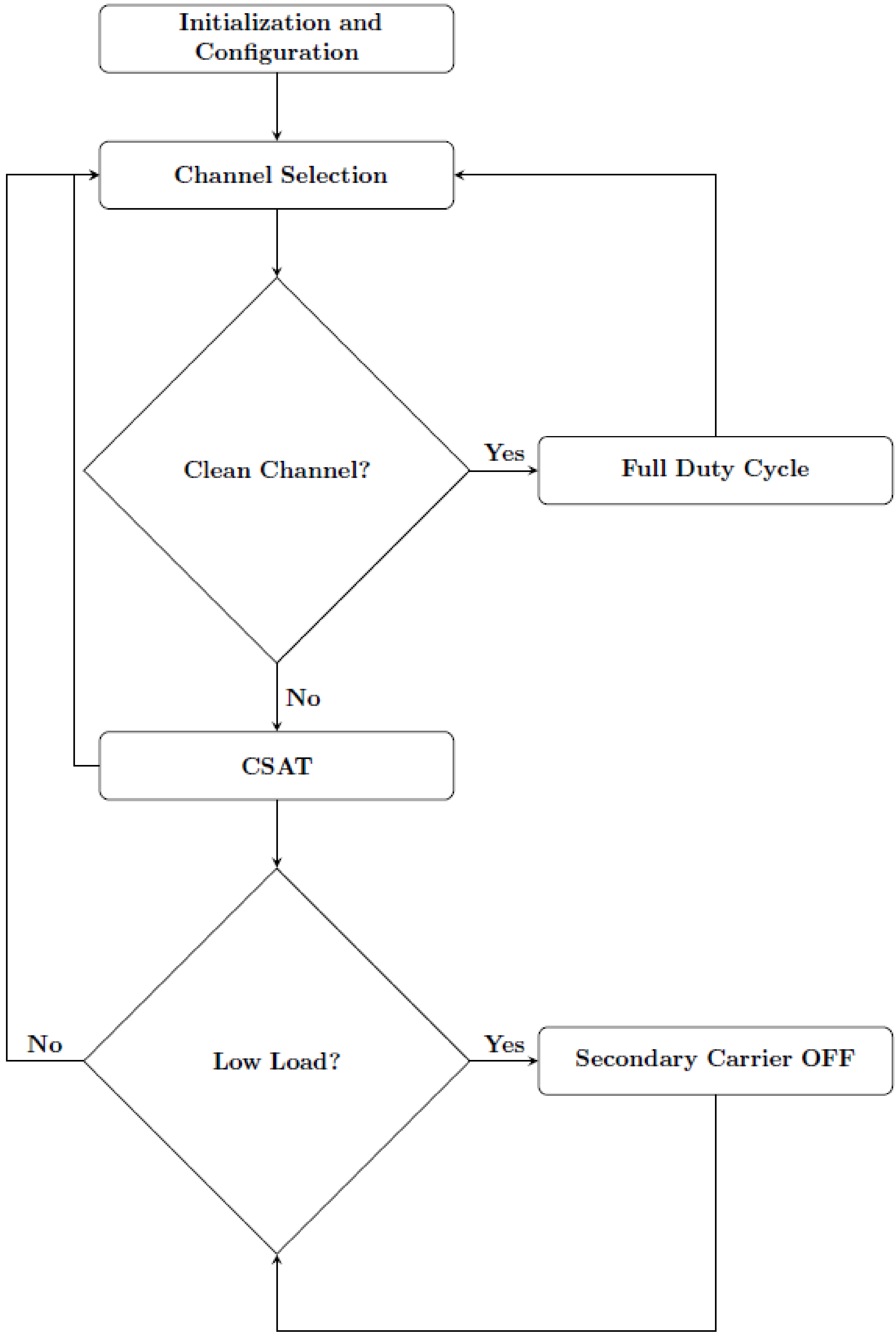


Figure 1.3: Coexistence flow chart for LTE-U [100].

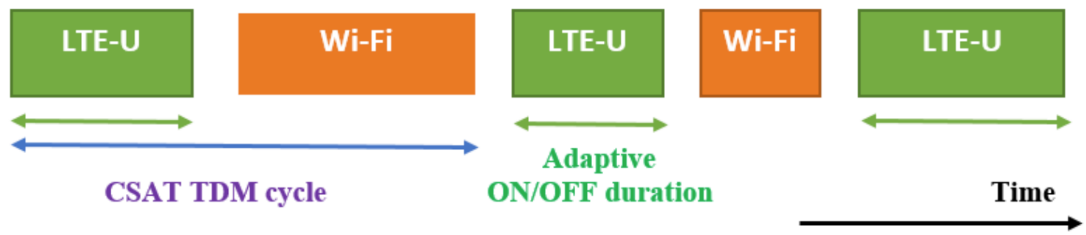


Figure 1.4: CSAT mechanism.

changes to the LTE specification and it is attractive where there are free available channels to increase the capacity in a short term with a fair coexistence with Wi-Fi networks. On the other hand, LTE-U duty-cycling has some drawbacks such as the controlling of the duty cycle being decided by the LTE-U device, which does not give the Wi-Fi network any opportunity or mechanism to influence the amount of transmission opportunities it receives. Thus, the Wi-Fi devices have to adapt to this cycle set by LTE-U which may degrade the performance of Wi-Fi network [96, 113].

Overall, it is worth mentioning that LTE-LAA enables a more fair coexistence than LTE-U (in terms of throughput and latency) over unlicensed bands at the expense of a significantly increased design complexity [114, 115]. On the other hand, LTE-U does not need modifying the LTE PHY/MAC layers since no LBT mechanism is needed [116]. However, different mechanisms are used for better coexistence of LTE-U/Wi-Fi technologies over unlicensed bands such as carrier selection, ON/OFF switching, and Carrier Sense Adaptive Transmission (CSAT) [117], which are already part of the legacy 3GPP standard and enable a straightforward deployment in existing networks. LTE-U depends on a duty-cycling technique with a light sensing scheme (i.e., CSAT) to adapt the DC for LTE. Moreover, LTE-U employs adaptive DC based on CSAT to adapt the ON/OFF duration for LTE channel access [118]. In general, LTE-U is significantly simpler than LAA, which makes of it a more attractive candidate in scenarios where simplicity and low cost are essential.

1.1.7 LTE Licensed Assisted Access (LTE-LAA)

In some countries, such as Europe and Japan, the LBT function is mandatory for the transmission over the unlicensed bands. LTE-LAA is the version of LTE in the unlicensed spectrum which was proposed in 3GPP Release 13 for the Downlink (DL). The main feature of LTE-LAA is that it uses the LBT mechanism before transmission, which needs some modifications to the LTE air interface. Moreover, LAA uses the CA concept which aggregates carriers from licensed and unlicensed bands. In particular, CA aggregates the Primary Cell (PCell) on licensed carrier and the Secondary Cell (SCell) on unlicensed carrier [100]. In Release 14, the Uplink (UL) scenario was introduced in the context of enhanced LAA (eLAA).

In the licensed LTE, no such frame exists to detect the collision and there is no LBT mechanism [119]. However, there is a major difference between the MAC layers of Wi-Fi and LTE, which yields some challenges in the coexistence of these two technologies in the unlicensed spectrum. The main challenge is that if LTE coexists with Wi-Fi on the same unlicensed band without any fair mechanism, then the performance of Wi-Fi will be affected by LTE transmission, because of the continuous nature of LTE transmission which prevents the Wi-Fi transmission. On the other hand, Wi-Fi is designated to coexist with other networks by random backoff and channel sensing mechanism [119]. This problem is resolved in LTE-LAA by introducing an LBT mechanism in the LTE network similar to that used in Wi-Fi networks to control the channel access.

LAA uses an LBT mechanism, which is similar to the CSMA/CA scheme used by the Wi-Fi technology. A periodic check to sense the channel before transmission is mandatory. In particular, when a Base Station (BS) or a device needs a transmission, it should detect the energy level for a time equal to the Clear Channel Assessment (CCA) time period [94]. Thus, some modifications are necessary to the LTE air interface protocol. On the other hand, in LTE-LAA, LTE BSs should send a reservation signal to prevent Wi-Fi transmissions for the next frame. Moreover, LTE BSs cannot begin the transmission until this condition is satisfied, which can degrade the total aggregated throughputs for both technologies due to this control overhead.

The Carrier Aggregation (CA) concept is considered to aggregate carriers from licensed and unlicensed bands [100]. CA is one of the most important technologies in LTE advanced, where it increases the data rate, capacity, and user throughput. LAA can be used as an SDL data channel (i.e. downlink only) by using Frequency Division Duplex (FDD) or as a Time Division Duplex (TDD) data channel (i.e. downlink and uplink). The concept of LAA is that the primary carrier is always ON while the secondary carrier could be ON or OFF depending on channel availability and overall network traffic. In principle, operators will use unlicensed spectrum to offload traffic during periods of high volume of traffic in their networks when the licensed spectrum is not enough to meet these high traffic demands. CA is used to aggregate both licensed and unlicensed spectrum. Thus, the control signalling and some data will be carried through the primary, while certain level of data will be carried through the secondary [94, 120].

In the LBT algorithm in the unlicensed spectrum, a periodic check to sense the channel (listen) before transmitting (talk) is required. Thus, when a device or a BS needs to transmit, it has to detect the energy level at a certain time equal to the CCA period. The LBT procedure is a major feature for fair coexistence between LAA and Wi-Fi in the unlicensed spectrum as stated in the 3GPP TR 36.889, it also uses Energy Detection (ED) to determine the availability of the channel [122, 123].

3GPP TR36.889 defines the meaning of fair coexistence between LTE and Wi-Fi in the 5 GHz as “the capability of an LAA network not to impact Wi-Fi networks active on a carrier more than an additional Wi-Fi network operating on the same carrier, in terms of throughput and latency” [96, 124]. As a result, the design of LAA should take into account a broad range of considerations such as fair and effective coexistence mechanism with Wi-Fi, and the design should achieve a comparable performance between different LAA deployed by different operators in terms of throughput and latency.

A. Listen Before Talk (LBT) in LTE-LAA

Different results in the literature show that there is a severe impact on Wi-Fi network performance by deploying LTE with the Wi-Fi in the unlicensed spectrum without LBT capabilities, and this impact is greater than the impact of deploying another Wi-Fi network. Moreover, many studies show that the use of LBT is necessary for a fair coexistence between LTE and Wi-Fi in the 5 GHz band, but also the parameters and the design of this LBT algorithm play an important role in this fairness [124, 125].

However, LBT uses a CCA period which is considered the listening time of the channel to check the channel availability. Moreover, an energy detection threshold is specified by the regulatory requirements in the regions where LBT is mandatory for transmission over unlicensed spectrum [100]. Then, when a node receives energy above this threshold, the node assumes the channel is not available. This threshold can be changed adaptively in LAA especially for the DL. However, there is a difference in the design of LBT for LAA DL and LAA UL since the LAA UL is based on scheduled access which affects the User Equipment’s (UEs) channel contention opportunities [119].

3GPP designs different kinds of channel access schemes. Firstly, LBT without backoff, where the time duration of sensing the channel to be idle is deterministic. Secondly, LBT with a fixed contention window, where the transmission follows a fixed contention window by generating a random number N within a fixed contention window size. This random number N is used in the LBT algorithm to determine the sensing time duration. Thirdly, LBT with a variable contention window, where LBT uses a variable size for the contention window instead of the fixed one to determine the duration of sensing the channel to be idle before transmitting [96]. As a result, the eventual algorithm selected by the 3GPP TR 36.889 was that one which is considered similar to how Wi-Fi networks implement LBT and it is called Category 4 LBT. Many modifications were required to the PHY/MAC LTE to meet the LBT algorithm requirements such as discovery signals to discover and acquire access, LBT using CCA for regional requirements, beacon signals for channel reservation for transmission and a Hybrid Automatic Repeat Request (HARQ) protocol.

B. Category 4 (Cat 4) LBT in LTE-LAA

3GPP evaluated different algorithms for LBT to coexist LAA with Wi-Fi in the unlicensed spectrum. The eventual algorithm selected was Category 4 (Cat 4) LBT algorithm which is very similar to the LBT principle used by the IEEE 802.11 networks. In general, LAA performs a CCA to access the unlicensed band and the LAA Contention Window (CW) for the evolved NodeB (eNB) is adjusted with a variable size based on the HARQ ACK feedback. The procedure is shown in Fig. 1.5. Specifically, the LAA eNB may transmit the data after sensing the channel to be idle for the initial CCA (iCCA) (e.g., 34μs) duration; otherwise, the extended CCA (eCCA) stage begins. In an eCCA, the channel is observed by the LAA eNB for the duration of a random backoff factor N multiplied by the CCA slot time duration (e.g., 9μs). N defines the number of observed idle slots that need to be sensed before transmission and it is randomly selected as $N \in [0,\ q\text{-}1]$ and the value is stored in a counter, where q-1 represents the upper bound of the CW, which varies according to an exponential backoff. When the channel is free, another eCCA duration (e.g., 9μs) starts and decrements N if the channel is free. When N reaches zero, the LAA eNB begins the transmission. If the LAA eNB needs another transmission, the eCCA stage is performed again. The CW size q-1 is initialised with 15 and it is exponentially increased based on the HARQ Acknowledgment Control Response (ACK) feedbacks. In particular, if 80% of the HARQ feedbacks from the first subframe of the latest transmission are Negative ACKs (NACKs), q is doubled and the CW size is updated to be $q\text{-}1 = 31$. Then, the CW size is updated again to be 63 if 80% of the HARQ feedbacks are still NACKs. Otherwise, the CW size is reset to the minimum (i.e., q-1 = 15) upon the absence of 80% NACKs condition. Thus, in Cat 4 LBT, the LAA CW size, q-1, varies between {15, 31, 63} based on the received HARQ reports.

1.2 Motivation and Objectives

Recently, due to the dramatic usage of mobile devices to access the internet, including smartphones, tablets and laptops, spectrum sharing has attracted mobile operators as a key solution due to the cost and the scarcity of the licensed spectrum. Unlike the licensed spectrum, unlicensed spectrum is free to access by anyone as long as a transmit power and timing constraint is satisfied [126]. On the other hand, this spectrum is mainly occupied by the Wi-Fi technology. Due to the wide available unlicensed spectrum over the unlicensed 5 GHz band, LTE networks have been recently deployed to operate over the unlicensed spectrum [96].

Wi-Fi technology defines a Distributed Coordination Function (DCF) for sharing access to the channel based on the CSMA/CA scheme [99]. In particular, each Wi-Fi node should listen to the channel before transmission to check the channel availability. However, LTE has a centralized control architecture (i.e., no sensing scheme). Thus, deploying LTE with Wi-Fi without any coexistence mechanisms in the unlicensed spectrum will affect Wi-Fi performance severely due to LTE transmission.

Current research aims to implement mechanisms that enable the coexistence of LTE and Wi-Fi in a fair manner. The main definition of "fairness" as defined by 3GPP for the coexistence mechanisms comprises that LTE-LAA network should not impact Wi-Fi network more than an additional Wi-Fi network operating on the same carrier. Taking the latest 3GPP LBT algorithm which is Category 4 LBT (Cat 4 LBT), it should be noticed that the coexistence performance of LTE-LAA and Wi-Fi in the 5 GHz band does not perfectly match the main definition of the fairness as defined by the 3GPP TR 36.889 [96] and there is a degradation in the Wi-Fi performance due to this coexistence. This degradation is due to a few potential drawbacks in the Cat 4 LBT algorithm which are described in Chapter 3.

The main objectives of this study are to investigate the impact of the various design parameters of LTE on the coexistence of LTE and Wi-Fi networks over the unlicensed 5 GHz band and to develop new solutions that can improve the performance of mobile LTE networks operating in unlicensed 5 GHz bands while effectively providing a true

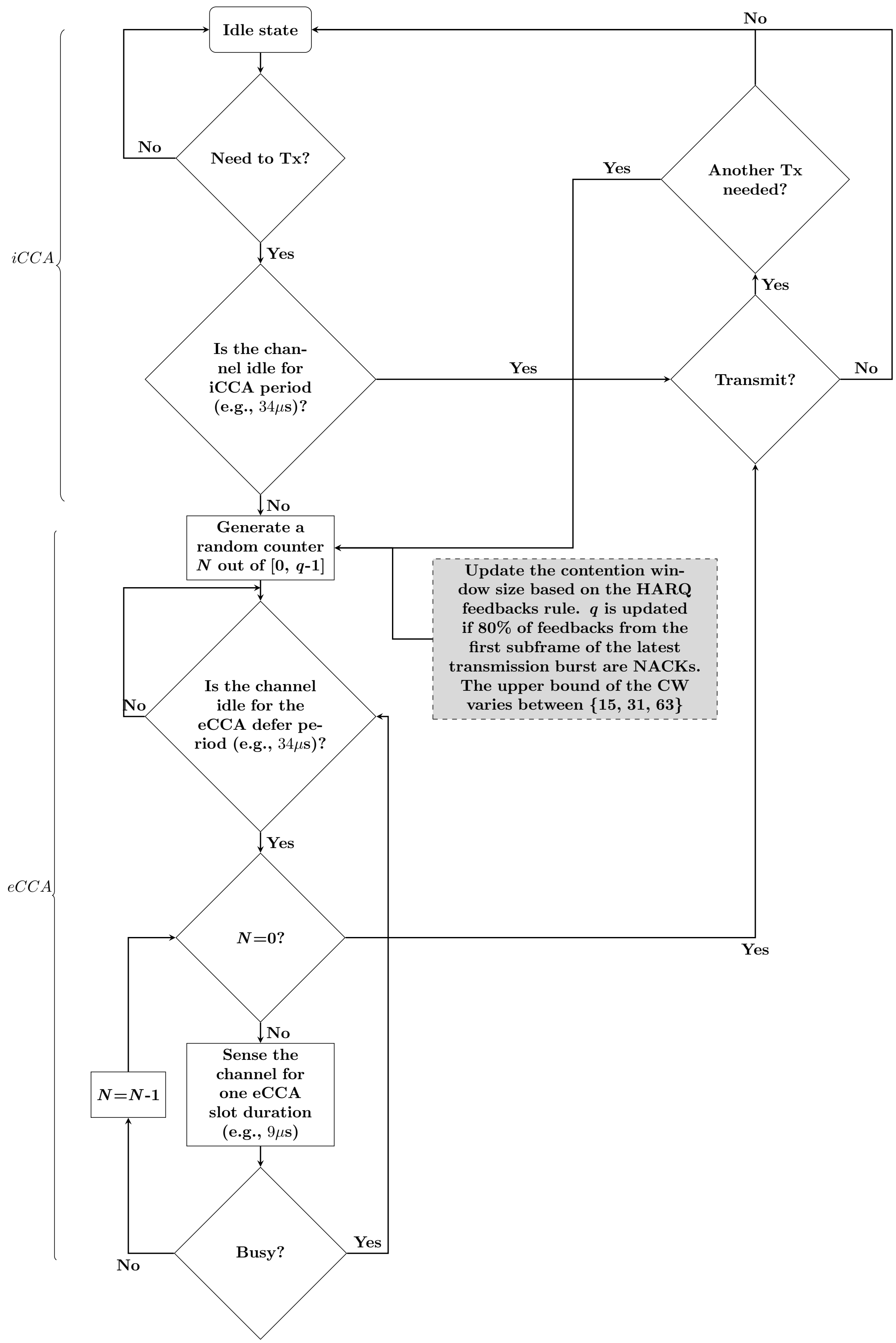


Figure 1.5: 3GPP Cat 4 LBT algorithm [96].

fair coexistence with Wi-Fi networks. To this end, both LTE-U and LAA technologies will be considered and enhanced with novel solutions. The main novelty of this work is the exploitation of the knowledge of Wi-Fi activity statistics to adapt/select various design parameters of LTE for improved LTE/Wi-Fi coexistence. This information is readily available with the existing technology but, to the best of the author's knowledge, has not been exploited in the context of LTE/Wi-Fi coexistence. This research will show that by a smart exploitation of this information it is possible to provide significant performance improvements for LTE networks while at the same time providing true fairness guarantees to the existing Wi-Fi networks in the 5 GHz band.

1.3 Thesis Contributions

In this dissertation, the focus is on LTE-U and LTE-LAA given that they represent the simplest unlicensed LTE approach and the most promising unlicensed LTE approach to achieve fairness, respectively. The main contribution of this dissertation is the exploitation of the activity statistics of the Wi-Fi network for an adequate configuration and operation of LTE-U and LTE-LAA over unlicensed spectrum. A distinguishing feature of the methods developed in the context of this dissertation is the ability to accurately capture the statistical properties of spectrum usage observed in real channels to allow a more fair coexistence between LTE and Wi-Fi networks over unlicensed spectrum. The development and validation of the proposed methods rely on the activity statistics of the existing Wi-Fi network that have been obtained by allowing a heterogeneous coexistence (i.e., Wi-Fi and Wi-Fi) over the same unlicensed band. The proposed methods can be helpful for some indoor real-world scenarios such as airports and shopping centres where mobile operators may not be able to always provide the required capacity. Thus, this problem can be solved by deploying Wi-Fi APs for such indoor environments.

The main contributions of this dissertation are as follows:

1. An exhaustive comparison analysis between LTE-U and LTE-LAA is provided when they are deployed with Wi-Fi over the unlicensed 5 GHz band. In particular, fair coexistence mechanisms of LTE and Wi-Fi technologies in the unlicensed 5 GHz band are discussed to achieve the best performance for both technologies. Moreover, the impact of changing some design parameters on LTE and Wi-Fi performances are investigated.

2. A novel approach to select a fixed Duty Cycle (DC) for LTE-U in coexistence with Wi-Fi technology over the 5 GHz band is proposed based on the Wi-Fi activity statistics of the ON/OFF time periods. Moreover, two methods to allocate the blank subframes within the LTE-U frames are proposed based on the Wi-Fi activity statistics.

3. The activity statistics of the existing Wi-Fi network are exploited for an adequate configuration and operation of LTE-LAA. Specifically, two dynamic Contention Window (CW) methods for LAA are proposed to improve the performance of LAA/Wi-Fi coexistence based on the 3GPP fairness definition. In particular, the activity statistics of the existing Wi-Fi network are exploited to set the upper bounds of the LAA CW, as opposed to the 3GPP Cat 4 LBT method, which considers a limited set of fixed upper bounds for the LAA. Moreover, a static CW method for LAA is proposed where the activity statistics of the existing Wi-Fi network are exploited to select a single fixed upper bound for the LAA CW instead of using variable upper bounds for the LAA CW size as considered in the 3GPP Cat 4 LBT method. Finally, various variants are proposed to select the lower bound of the CW of LAA based on the minimum and mode of the activity statistics of the existing Wi-Fi network. Moreover, a fixed waiting time method for LAA is proposed based on these variants as well.

4. A novel dynamic Transmission Opportunity (TxOP) period approach is proposed where the observed Wi-Fi transmission pattern is exploited to configure the maximum TxOP length for LAA using a dynamic scheme. While different approaches to configure and adapt the LAA CW have been proposed in the literature, the TxOP period has always been considered as a fixed parameter. In this work the idea to adapt this parameter dynamically based on the Wi-Fi activity statistics is proposed.

It is worth noting that the idea of deploying mobile networks in unlicensed spectrum bands was first introduced in the context of the 4G LTE technology and is also considered in the context of 5G New Radio in Unlicensed bands (5G NR-U) [104, 105]. At the time this research started, 5G was still an immature technology under development and the concept of 5G NR-U was still at a very preliminary stage. Therefore, LTE was selected at the beginning of this research as the mobile technology over which the proposed methods have been developed and assessed. During the course of this research, the 5G NR-U technology completed its first development, however LTE was still used throughout the rest of the research presented in this dissertation. The introduction of 5G NR-U provides some enhancements in the spectrum coexistence with Wi-Fi compared to the 4G LTE-U/LAA technology. The most significant difference is that the flexible numerology introduced in 5G NR allows a better time granularity in the channel access, with mini-slots as short as 125 μs (as opposed to the 1-ms time frame used by 4G LTE). This enables 5G NR-U to use a gap-based mechanism to access the unlicensed channel (where the contention procedure is carried out to finish at the beginning of a new mini-slot), which is more spectrum efficient than the reservation signal mechanism typically implemented by 4G LTE-U/LAA (where a dummy signal is transmitted to keep the channel busy and avoid any potential Wi-Fi access until the beginning of the new LTE frame). Besides this, the MAC LBT protocol remains largely the same, which is the main focus of this research, and therefore the main contributions, conclusions and findings of this research should still be valid and applicable in the context of 5G NR-U operating in 5 GHz and higher unlicensed spectrum bands. A repository for all codes that are used to implement the various proposed methods in the thesis is uploaded at GitHub platform and the codes are available on https://github.com/Alhulayil/LTE-WiFi-Coexistence.

1.4 Thesis Structure

The remainder of this Ph.D. dissertation is structured as follows. In Chapter 2, a detailed comparison between the coexistence of LTE-U/Wi-Fi and LTE-LAA/Wi-Fi scenarios is provided. In addition, a detailed description for the ns-3 simulator used in this research and the impacts of changing some design parameters on LTE and Wi-Fi performances are presented. In Chapter 3, methods for the Allocation of Almost Blank Subframes (ABS) with fixed Duty Cycle (DC) for improved LTE-U/Wi-Fi coexistence are provided. In specific, a new fixed DC approach to select the LTE-U DC for a fair coexistence between LTE-U and Wi-Fi is introduced, where two methods are implemented for allocating the blank subframes for better performance. In Chapter 4, novel LAA waiting and transmission time configuration methods for improved LTE-LAA/Wi-Fi coexistence are provided. In specific, various methods to adapt/select the waiting times for LAA and a dynamic approach to configure the transmission times for LAA are presented. Finally, the main conclusions and some suggestions for future work are summarised in Chapter 5.

1.5 List of Publications

The contributions of this thesis have been published in several international conferences and a journal. A complete list of publications along with the related contributions is listed below. It is worth noting that conference publication [C.3] below received the Best Paper Award at the 2019 International Conference on Wireless Networks and Mobile Communications (WINCOM 2019).

Journals

[J.1] **M. Alhulayil** and M. López-Benítez, "Novel LAA Waiting and Transmission Time Configuration Methods for Improved LTE-LAA/Wi-Fi Coexistence Over Unlicensed Bands," in *IEEE Access*, vol. 8, pp. 162373–162393, Sep. 2020.

International conferences

[C.1] **M. Alhulayil** and M. López-Benítez, "Coexistence Mechanisms for LTE and Wi-Fi Networks over Unlicensed Frequency Bands," in *2018 11th International Symposium on Communication Systems, Networks & Digital Signal Processing (CSNDSP)*, Budapest, Hungary, 2018, pp. 1–6.

[C.2] **M. Alhulayil** and M. López-Benítez, "Methods for the Allocation of Almost Blank Subframes with Fixed Duty Cycle for Improved LTE-U/Wi-Fi Coexistence," in *2019 International Conference on Wireless Networks and Mobile Communications (WINCOM)*, Fez, Morocco, 2019, pp. 1–6.

[C.3] **M. Alhulayil** and M. López-Benítez, "Static Contention Window Method for Improved LTE-LAA/Wi-Fi Coexistence in Unlicensed Bands," in *2019 International Conference on Wireless Networks and Mobile Communications (WINCOM)*, Fez, Morocco, 2019, pp. 1–6. **(Best Paper Award)**

[C.4] **M. Alhulayil** and M. López-Benítez, "Dynamic Contention Window Methods for Improved Coexistence Between LTE and Wi-Fi in Unlicensed Bands," in *2019 IEEE Wireless Communications and Networking Conference (WCNC 2019), 5th IEEE Interna-*

tional Workshop on Smart Spectrum (IWSS 2019), Marrakech, Morocco, 2019, pp. 1–6.

[C.5] **M. Alhulayil** and M. López-Benítez, "LTE/Wi-Fi Coexistence in Unlicensed Bands Based on Dynamic Transmission Opportunity," in *2020 IEEE Wireless Communications and Networking Conference (WCNC 2020), 6th IEEE International Workshop on Smart Spectrum (IWSS 2020)*, Seoul, South Korea, 2020, pp. 1–6.

Chapter 2

Performance Evaluation of LTE/Wi-Fi Coexistence Mechanisms in Unlicensed Bands

2.1 Introduction

Recently, mobile data traffic has rapidly grown which results in many challenges especially in the radio spectrum needs. Thus, deploying LTE over unlicensed bands is becoming an attractive area of research. In particular, the idea is to utilise the unlicensed spectrum by deploying mobile network base stations (typically, but not exclusively, small cells in indoor environments) over these unlicensed bands to coexist with Wi-Fi, radar, Bluetooth and possibly other mobile operators' networks. Based on the different advantages of deploying LTE in unlicensed spectrum such as high spectral efficiency and good performance of LTE in dense deployments, different contributions in the literature proposed different mechanisms to share the unlicensed spectrum by LTE and Wi-Fi networks in a fair manner [119, 127]. For example, the coexistence of LTE and Wi-Fi has been studied in the TV white space band in [128], the results show that LTE impacts Wi-Fi when the nodes are randomly deployed. While in [97], the authors proved that it is unfair to share the same channel between Wi-Fi and LTE nodes without a controlled procedure.

On the other hand, this coexistence between LTE and Wi-Fi technologies faces many limitations and challenges over these unlicensed bands. In this context, this chapter presents a coexistence analysis between LTE and Wi-Fi over the unlicensed 5 GHz band. The coexistence mechanism is studied by deploying different scenarios of LTE. The first scenario is by using LTE Unlicensed (LTE-U) duty-cycling, while the second one is by using LTE Licensed Assisted Access (LTE-LAA). In particular, simulation results using ns-3 simulator for the throughput and latency for different coexistence deployments are provided. The impact of changing some parameters on LTE and Wi-Fi performances are studied as well. The results of this chapter have been published in [116].

The rest of this chapter is organized as follows. The ns-3 network simulator, including Wi-Fi and LTE modules, is described in detail in Section 2.2. The scenarios considered in this study and the simulation methodology are presented in Section 2.3, while Section 2.4 provides and analyses the obtained results. Finally, Section 2.5 summarises and concludes the chapter.

2.2 ns-3 Simulator

The methods developed in this dissertation will be evaluated by means of simulators conducted with the ns-3.26 simulator. The ns-3 simulator is a discrete event network simulator targeted for research and educational purposes and to conduct simulation experiments. This simulator is open-source which allows researches to share their contributions. It is a new version network simulator and it is not a backward compatible extension of ns-2 simulator. Thus, the ns-3 does not support ns-2 applications [129].

Although ns-3 is a very complex simulator, there are many reasons to use it such as performing experiments or studies that are not possible to perform in real systems, controlling complicated systems and studying the behavior of these controlled systems, and knowing exactly how the networks work. ns-3 has many distinguished features compared to other network simulators. Firstly, it is built from many libraries that can be augmented together or with external software libraries while providing a single graphical user interface environment where all tasks are carried out. Secondly, external data analysers, visualization tools and animators can be used with ns-3. Thirdly, users can work on the command line using C++ and/or Python and the simulation scripts can be written in C++ or Python. Fourthly, ns-3 is mainly used in Linux systems, but it can be used for Free VSD and Cygwin (for Windows). Finally, it is free software with a wide community support.

Moreover, ns-3 is more attractive than ns-2 due to many reasons. Firstly, ns-2 has not had significant development in the main code while ns-3 is actively maintained with user's

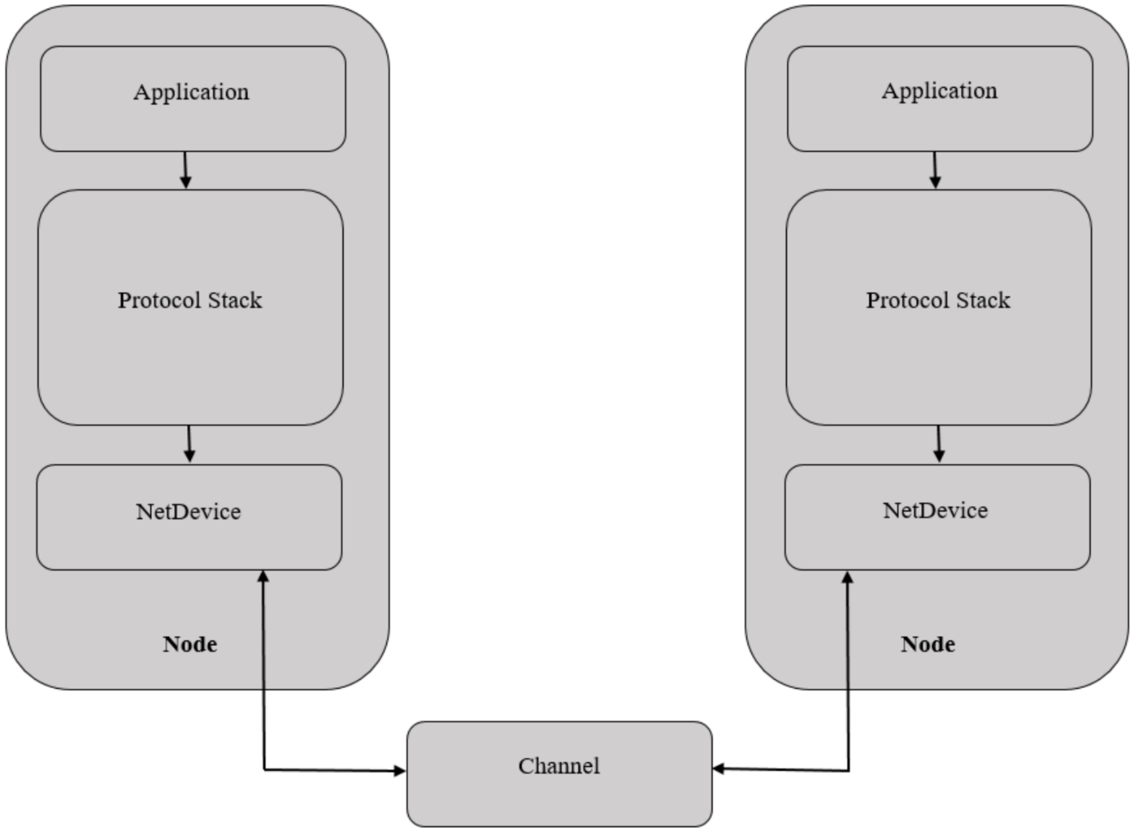


Figure 2.1: The basic model of ns-3.

mailing list. Secondly, ns-3 provides some features that are not available in ns-2 such as running real implementation code in the simulator. Thirdly, ns-3 has many detailed models in different research areas (such as LTE and Wi-Fi models). Finally, ns-3 has a lower base of abstraction than ns-2.

There are some fundamental objects within ns-3 which are considered the basics for any ns-3 model as shown in Fig. 2.1. The *Node* is the basic computing device abstraction in ns-3 which is represented by the class *Node*. The *Node* can be considered as a computer which will be loaded with some functions such as protocol stacks, applications or peripheral cards. While *Channel* is the physical connector between a set of nodes. Some of *Channel* versions are *PointToPointChannel*, *CsmaChannel* and *WifiChannel*, to mention just a few examples.

The *NetDevice* is a network card which can be plugged in an input/output interface of a node and it covers both the software driver and the simulated hardware. Thus, *NetDevice* is installed in a *Node* to enable the communications between *Nodes* in the simulation through *Channels*. There are different versions of the *NetDevice* such as *PointToPointNetDevice*, *CsmaNetDevice* and *WifiNetDevice*. While the *Application* is a packet generator or consumer which can run on a node and talk to a set of network stacks. As a result, in ns-3, several connections need to be arranged between *Nodes*, *NetDevices* and *Channels*.

There are many *Helpers* in ns-3 that help in creating *NetDevices*, assigning IP addresses, adding MAC addresses, installing *NetDevices* on Nodes, configuring the protocol stack and connecting the *NetDevices* to *Channels*.

2.2.1 ns-3 Wi-Fi Module

One of the *NetDevices* in the ns-3 is *WifiNetDevice* which creates models of 802.11-based infrastructure and ad hoc networks. ns-3 provides models for different flavours of 802.11 such as 802.11a, 802.11b, 802.11g, 802.11ac, 802.11n and 802.11s (both 2.4 GHz and 5 GHz bands) [130]. It has different propagation loss models, propagation delay models and control algorithms. Moreover, *WifiNetDevice* in ns-3 can coexist with other *NetDevices*, which is not implemented in ns-2.

The implementation of *WifiNetDevice* provides three sublayers of models, the PHY layer which is responsible for modelling the reception of packets and tracking energy consumption, the MAC low layer which models functions such as medium access (DCF, RTS/CTS and ACK), and the MAC high layer which implements non-time critical processes such as beacon generations and state machines.

On the other hand, there are a few limitations in the Wi-Fi module in NS-3 such as the interference from other technologies is not modelled, MIMO systems are not supported and there is only one channel model (*ns3::YansWifiChannel*). Thus, only Wi-Fi nodes can be attached to the *ns3::YansWifiChannel*. Therefore, other technologies such as LTE are not allowed, which requires some modifications to the default/basic models available in ns-3.

2.2.2 ns-3 LTE Module

The ns-3 LTE module was developed by LENA project to design and evaluate the performance of several aspects of LTE systems such as DL and UL LTE MAC schedulers, inter-cell interference coordination solutions, radio resource management algorithms, cognitive LTE systems, radio level performance, dynamic spectrum access, etc. Moreover, the LTE module provides only Single Input Single Output (SISO) systems but it supports the mobility and handover features [131].

As a result, the need for a new module that can allow the coexistence between Wi-Fi and LTE forced the Wi-Fi Alliance to improve ns-3 modules to facilitate studies about the coexistence. The new coexistence module was developed in three phases. In phase 1: a new Wi-Fi Spectrum-based physical layer has been produced to allow the coexistence between Wi-Fi and LTE devices on the same ns-3 channel. In phase 2: LBT algorithm for LTE has been provided. While in phase 3: new features have been developed to include the voice application model and to update the interaction between LAA scheduler and channel access manager by using the category 4 LBT algorithm and to provide MIMO systems [129].

2.3 Simulation Methodology and Setup

The methodology for evaluating the fairness mechanism follows the procedure described in 3GPP TR 36.889 [96]. In particular, Category 4 LBT for LAA has been implemented. Two operators have been considered using the same channel in the 5 GHz band. The performance has been evaluated in three scenarios. In scenario 1, both operators deploy Wi-Fi technology. In scenario 2, one operator deploys LTE-U (Duty-Cycling without LBT) technology and the other operator deploys Wi-Fi technology. In scenario 3, one operator deploys LTE-LAA (Category 4 LBT) technology and the other operator deploys Wi-Fi technology.

In this work, an indoor scenario is considered rather than an outdoor scenario because it is the most common scenario where this kind of coexistence might happen. In particular, Wi-Fi technology cannot be used to provide coverage over large geographical areas since it is a short range connectivity technology. On the other hand, LTE technology is used in such areas to provide better coverage and to meet the high traffic demand. An indoor scenario in a single floor building is adopted as specified by 3GPP by considering two operators; operator A (Wi-Fi) and operator B (Wi-Fi, LTE-U or LAA) using the same 20 MHz channel over the unlicensed 5 GHz band [96]. The indoor simulation scenario is shown in Fig. 2.2. Operator A (Wi-Fi) deploys four Access Points (APs) while operator B (LTE) deploys four eNBs. All the base stations (i.e., APs and eNBs) are equally spaced and centred along the shorter dimension of the building. Moreover, each operator deploys

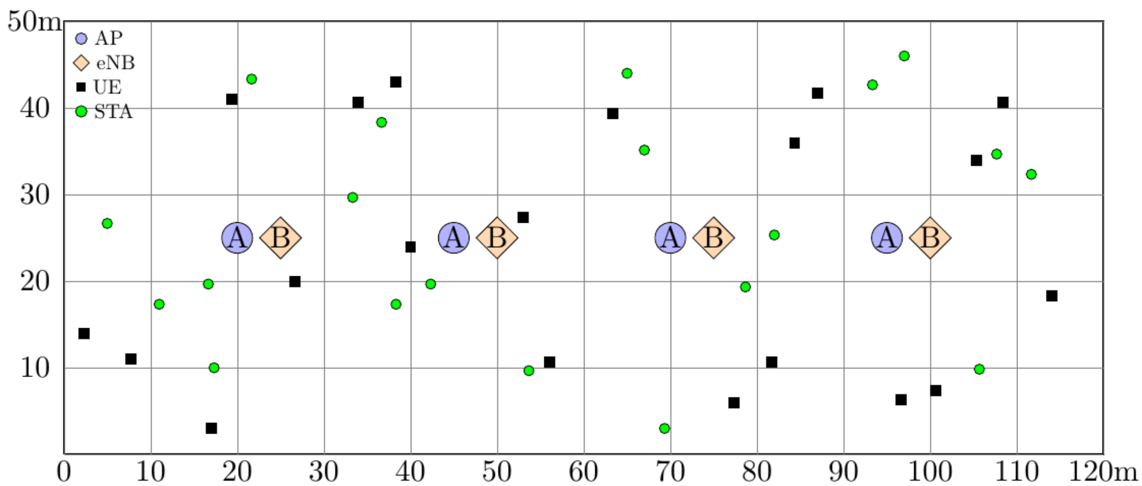


Figure 2.2: Indoor layout with two operators (operator A and operator B) with 4 cells per operator and 5 STAs/UEs per cell.

20 stations (STAs)/User Equipments (UEs) randomly distributed in a one floor building with a rectangular area. All base stations (i.e., APs and eNBs) and users (i.e., STAs and UEs) are equipped with two antennas for 2x2 MIMO operation. The traffic is modelled as a File Transfer Protocol (FTP) Model 1 operating over User Datagram Protocol (UDP) considering DL scenario. This model simulates file transfers according to a Poisson process with an arrival rate $\lambda = 1.5$ packets/second with simulation duration of 240 seconds and the file size considered is 0.5 MB. Notice that the packet size of 0.5 MB is the size of the Protocol Data Unit (PDU) at the application layer. The ns-3 simulator implements the whole set of layers of the protocol stack and these packets are split into smaller pieces of data for transmission according to the PDU size at each level of the protocol stack. The details of the employed simulation parameters are shown in Table 2.1 along with the 3GPP reference scenario.

The coexisting Radio Access Technologies (RATs) detect each other based on an Energy Detection (ED) principle. Wi-Fi nodes can detect other Wi-Fi nodes at –82 dBm and LAA nodes at –62 dBm. On the other hand, LAA nodes can detect Wi-Fi nodes at –72 dBm. This means that Wi-Fi will defer to weaker Wi-Fi signals sensed on the channel compared to LTE signals, which are detected at –62 dBm. The parameter (TxOP) which describes the maximum length of transmission is set to 8 msec and is configurable. The Contention Window (CW) is adjusted based on the received HARQ feedback where the HARQ declares

Table 2.1: Simulation parameters (see [96, Annex A.1.1] for details).

	3GPP TR 36.889	**ns-3 simulator**
Network layout	Indoor scenario	Indoor scenario
System bandwidth	20 MHz	20 MHz
Carrier frequency	5 GHz	5 GHz (Ch.36)
Max. total BS Tx power	18/24 dBm	18 dBm
Max. total UE Tx power	18 dBm	18 dBm
Pathloss, shadowing & fading	ITU Indoor/Hotspot	IEEE 802.11n
Antenna pattern	2D omni-D	2D omni-D
Antenna height	6 m	6 m for LAA
UE antenna height	1.5 m	1.5 m for LAA
Antenna gain	5 dBi	5 dBi
UE antenna gain	0 dBi	0 dBi
UE dropping	Randomly	Randomly
Traffic model	FTP model 1 & 3	FTP model 1

a collision and then the CW size is updated if Z=80% of feedbacks from the first subframe of the latest transmission burst are NACKs. Otherwise, the CW size is reset to 15 since the upper bound of the CW varies between {15, 31, 63} based on Category 4 LBT. As mentioned before, based on the 3GPP TR 36.889, the main performance metrics in the coexistence mechanisms are the throughput and latency. As the results will show, different loads have been simulated by changing different parameters to study the effects of changing these parameters on the coexistence performance.

2.4 Simulation Results

The amount of data received on a flow divided by the time interval between the first and last packet of the flow as observed at the IP layer is defined as the throughput. While the latency is an expression of how much time it takes for a packet of data to get from one point to another. As illustrated in Fig. 2.3, the plots are Cumulative Distribution Functions (CDFs) of file transfer throughputs and latencies observed during the simulation for different deployments; Case (a): Wi-Fi with Wi-Fi, Case (b): LTE-U with Wi-Fi and

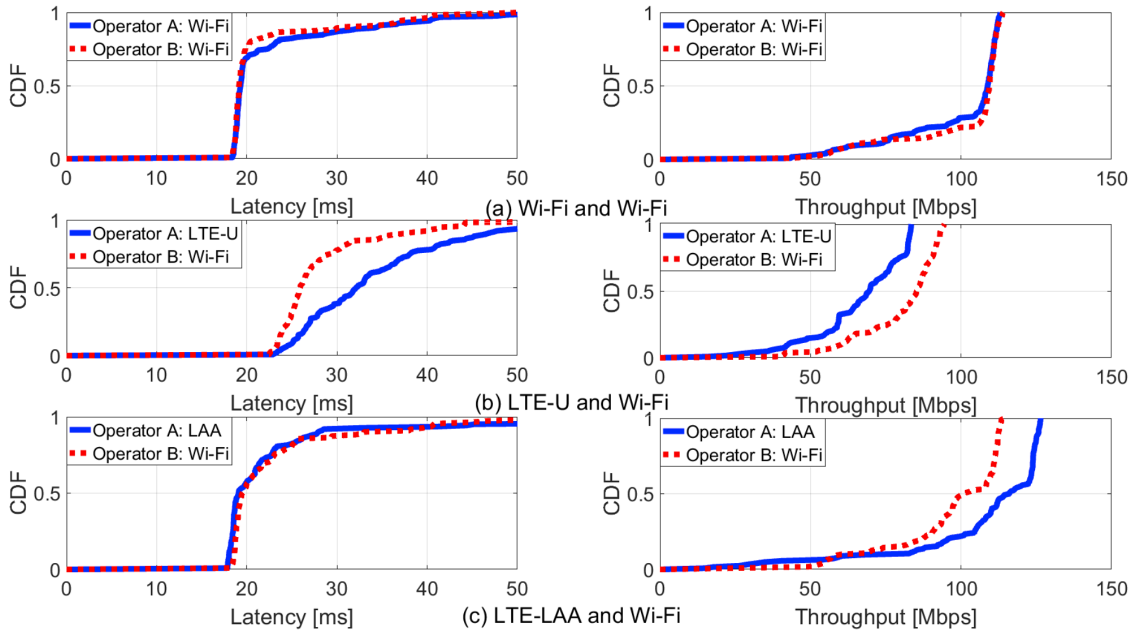


Figure 2.3: Throughputs and latencies for different coexistence deployments: (a) Wi-Fi and Wi-Fi, (b) LTE-U (DC=0.5) and Wi-Fi, (c) LTE-LAA and Wi-Fi.

Case (c): LTE-LAA with Wi-Fi. It can be seen that when only two Wi-Fi networks coexist, they achieve similar performance. An ideal LTE coexistence mechanism should allow the Wi-Fi network to achieve the same performance shown in Fig. 2.3a. Therefore, this result can be used as a reference to evaluate new proposed LTE mechanisms. In particular, the more effective (fair) LTE mechanism is in Case (c), i.e. the closer Wi-Fi performance to the results shown in Fig. 2.3a, where the deployment is LTE-LAA with Wi-Fi since there is a controlled coexistence based on Category 4 LBT. While in Case (b) there is a degradation in the Wi-Fi performance due to the uncontrolled mechanism of LTE-U. Moreover, in Case (c), LTE-LAA latency averages between (17-28) ms, with a few outlier values that range up to 118 ms. Wi-Fi latencies are similar with a maximum latency of 50 ms. Based on the obtained results, it can be concluded that LTE-LAA provides a more fair coexistence between LTE and Wi-Fi than LTE-U.

Different CDFs of throughputs and latencies are depicted in Fig. 2.4 for Case (b) deployment (LTE-U and Wi-Fi) with different duty cycles to study the effect of this parameter on the coexistence performance. It can be noted that the performance of LTE improves as the LTE duty cycle increases because this allows LTE to transmit more often,

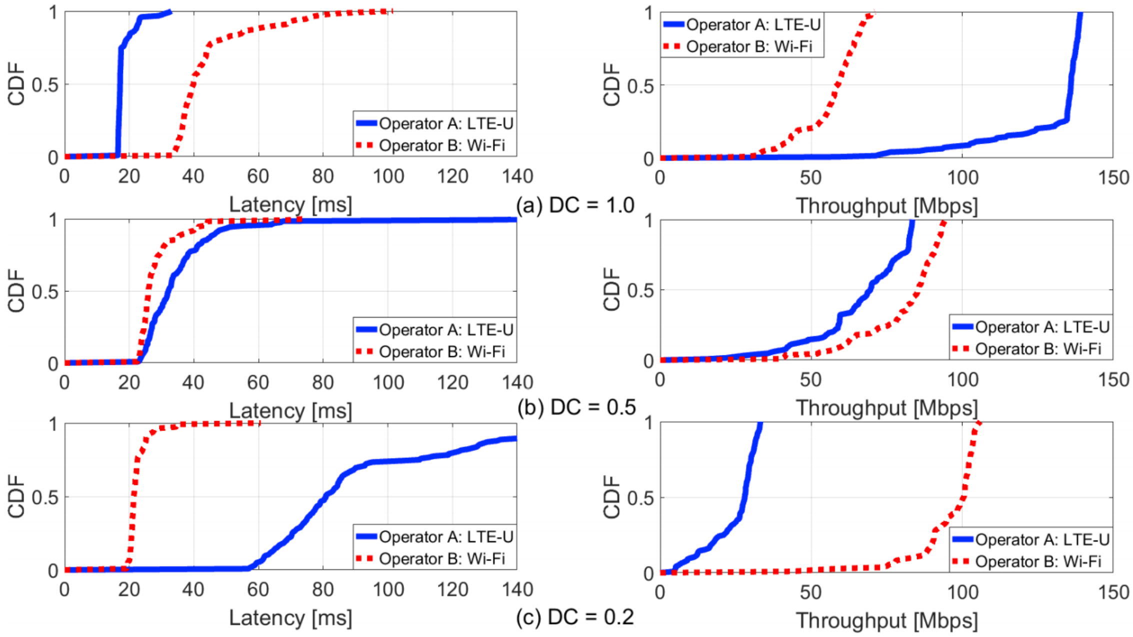
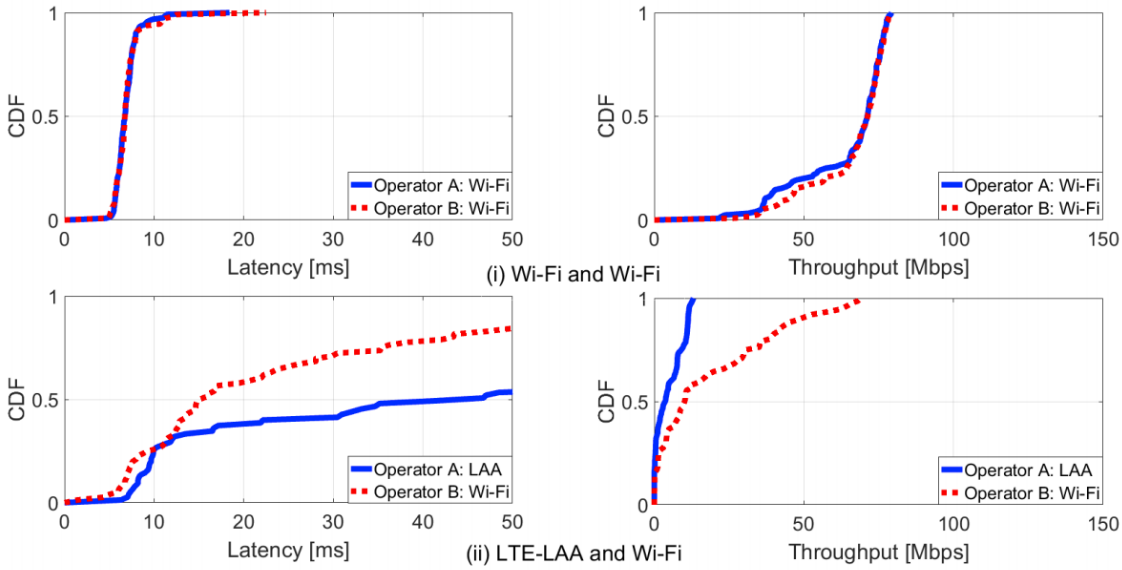


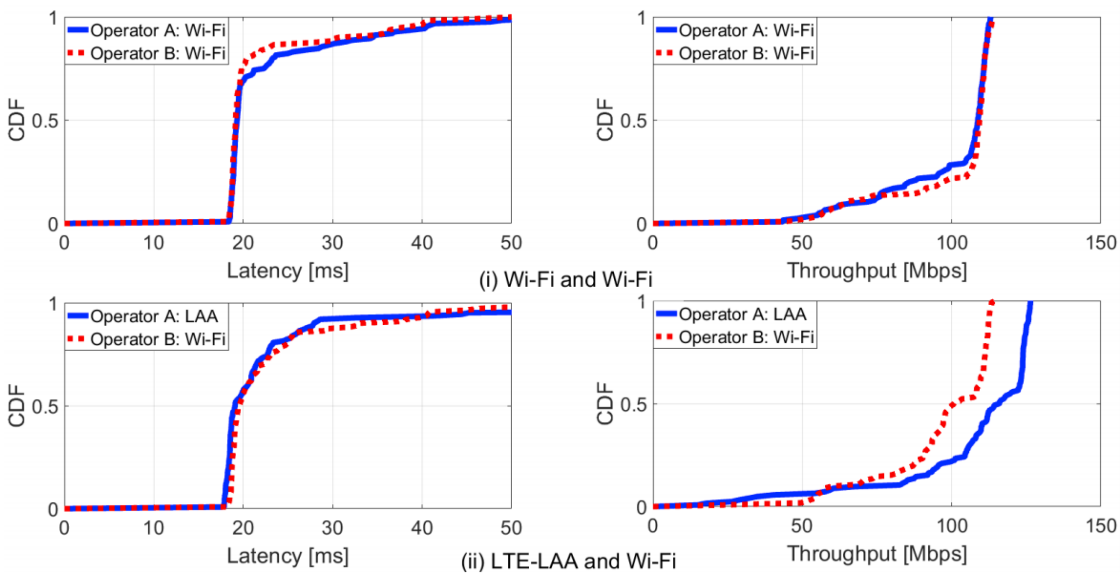
Figure 2.4: Throughputs and latencies for several DC values of LTE-U: (a) DC = 1.0, (b) DC = 0.5, (c) DC = 0.2.

however there is a degradation in the performance of Wi-Fi as well. On the other hand, a fair coexistence can be seen when the duty cycle is set to 0.2. Basically, Fig. 2.4 shows that with LTE-U, the only way to provide a fair coexistence is by keeping the DC very low (e.g. DC=0.2), however in this case the LTE performance is degraded (i.e., low throughput and high latency) and the access to the unlicensed band may not provide the sought increased capacity and performance for LTE.

Fig. 2.5 depicts the CDFs of throughputs at IP layer and latencies for Transmission Control Protocol (TCP) and User Datagram Protocol (UDP). Firstly, low throughput is noticed for LTE-LAA and Wi-Fi TCP case compared with the Wi-Fi and Wi-Fi TCP case due to the typical protocol stack delays in LTE; the delay can be high because of the need to send buffer status reports, receive an uplink Data Centre Interconnect (DCI) message on the DL, and scheduling the ACK for transmission on a future subframe. Secondly, there is a performance degradation in the Wi-Fi network in the TCP case compared with the UDP case. This degradation is due to the increased channel occupancy time that LTE-LAA uses when TCP is used. Both aspects affect the behaviour of the TCP congestion



(a) TCP



(b) UDP

Figure 2.5: Throughputs and latencies for LAA: (a) Using TCP, (b) Using UDP.

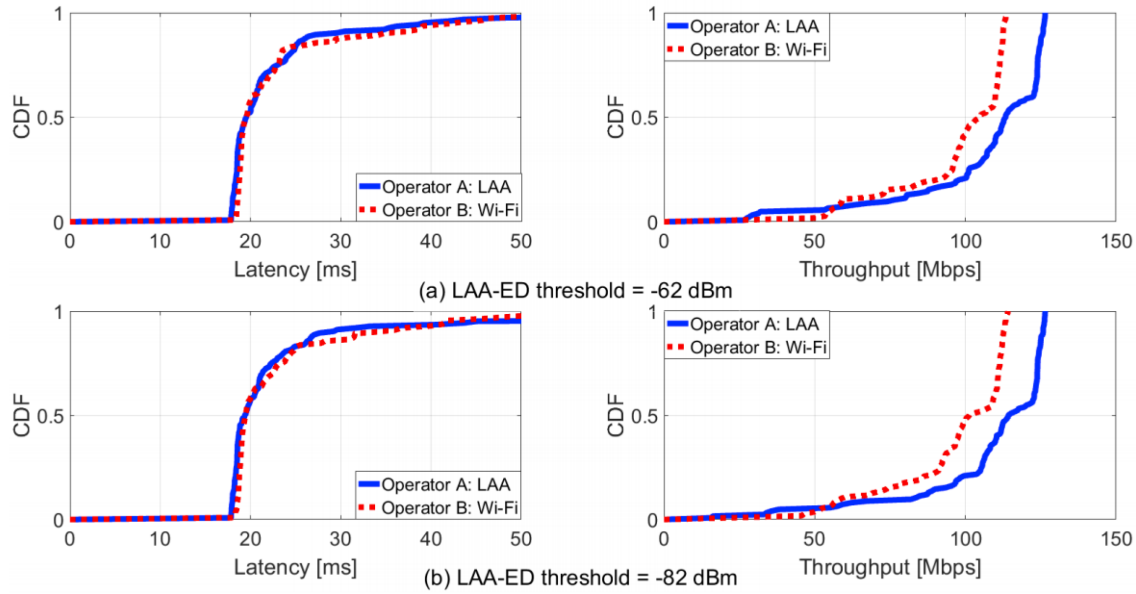


Figure 2.6: Throughputs and latencies for LAA using different LAA ED thresholds: (a) –62 dBm, (b) –82 dBm.

control mechanism, hence the degraded performance. It is also worth mentioning that after simulating and setting many parameters, it was observed that the coexistence performance is not affected by changing parameters such as the LAA ED threshold, LBT TxOP or the Z parameter associated to the HARQ based rule for the CW size update. The practical impact of these parameters is not significant. As an example, different settings for the LAA ED threshold parameter are shown in Fig. 2.6. Moreover, the impact of other parameters has been studied such as Z parameter, number of users per cell, LAA TxOP period of LBT and arrival rate. The impact of these various paramters are shown in Figs. 2.7–2.10.

In summary, based on the obtained simulation results, it can be concluded that LAA provides a more fair coexistence than LTE-U since it allows the existing Wi-Fi network to experience a throughput and latency more similar to that experienced when it coexists with another Wi-Fi network instead of an LTE network. As a result, LAA can be considered as a preferred approach in terms of coexistence fairness.

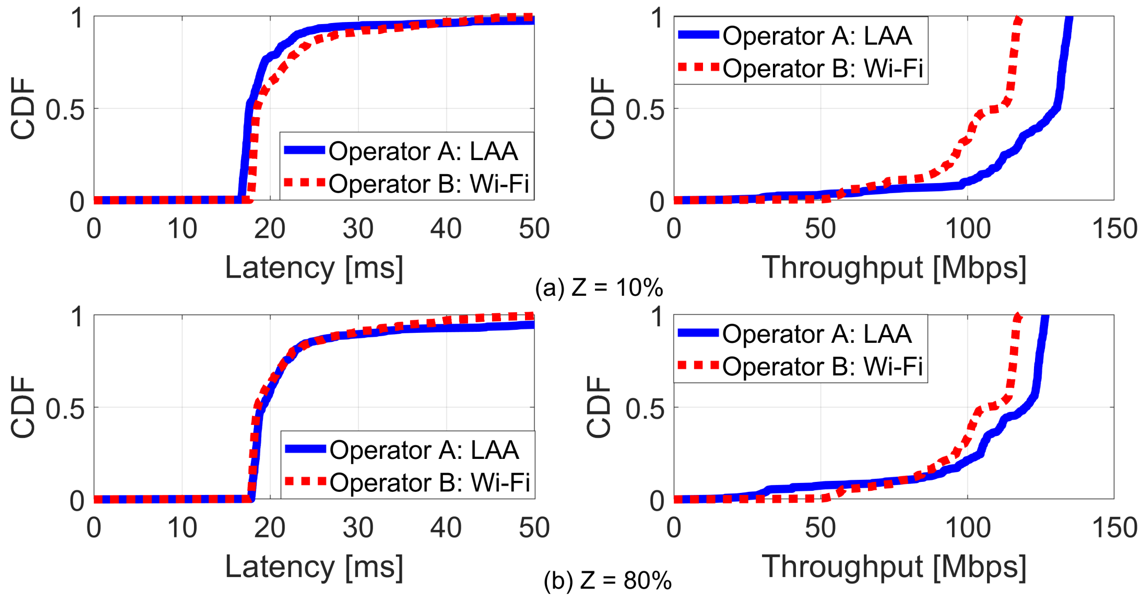


Figure 2.7: Throughputs and latencies for LAA using different Z parameter: (a) Z = 10%., (b) Z = 80%.

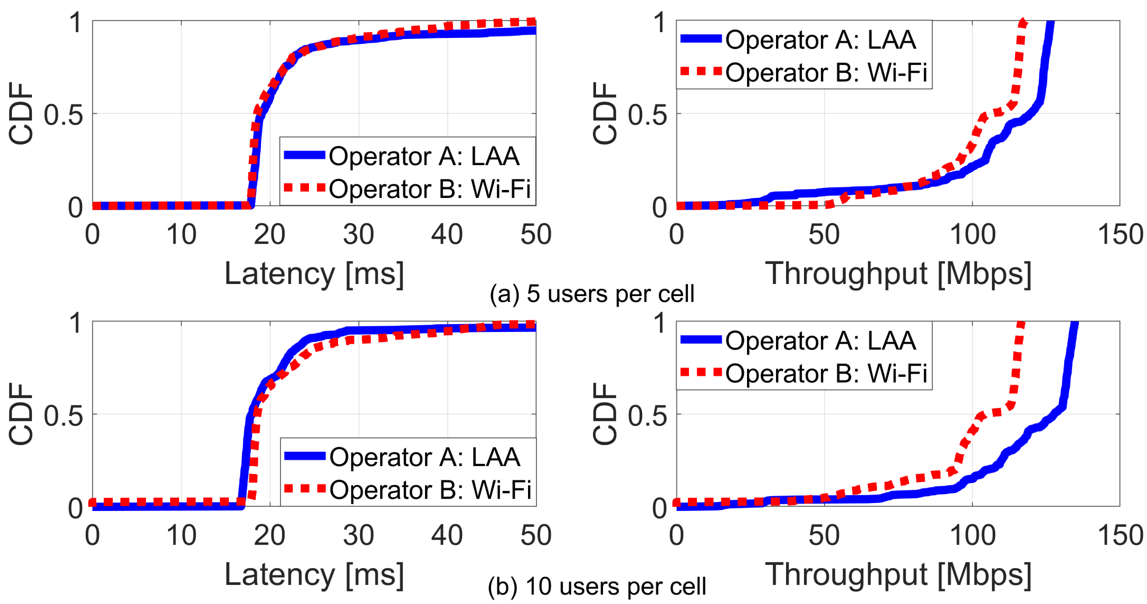


Figure 2.8: Throughputs and latencies for LAA using different number of users: (a) 5 users per cell., (b) 10 users per cell.

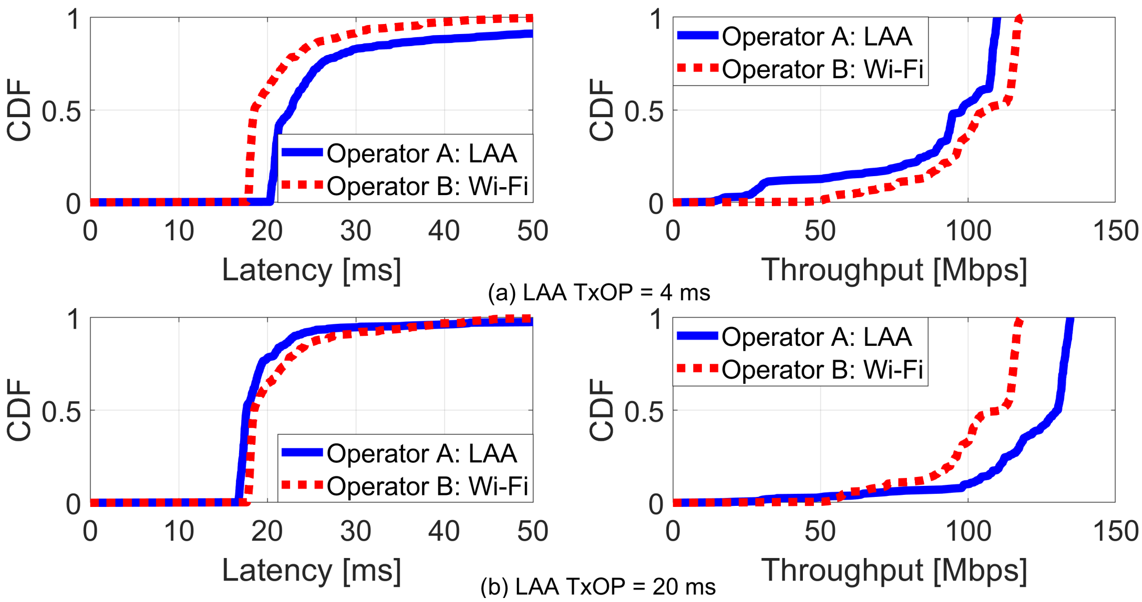


Figure 2.9: Throughputs and latencies for LAA using different LAA TxOP periods: (a) LAA TxOP = 4 ms., (b) LAA TxOP = 20 ms.

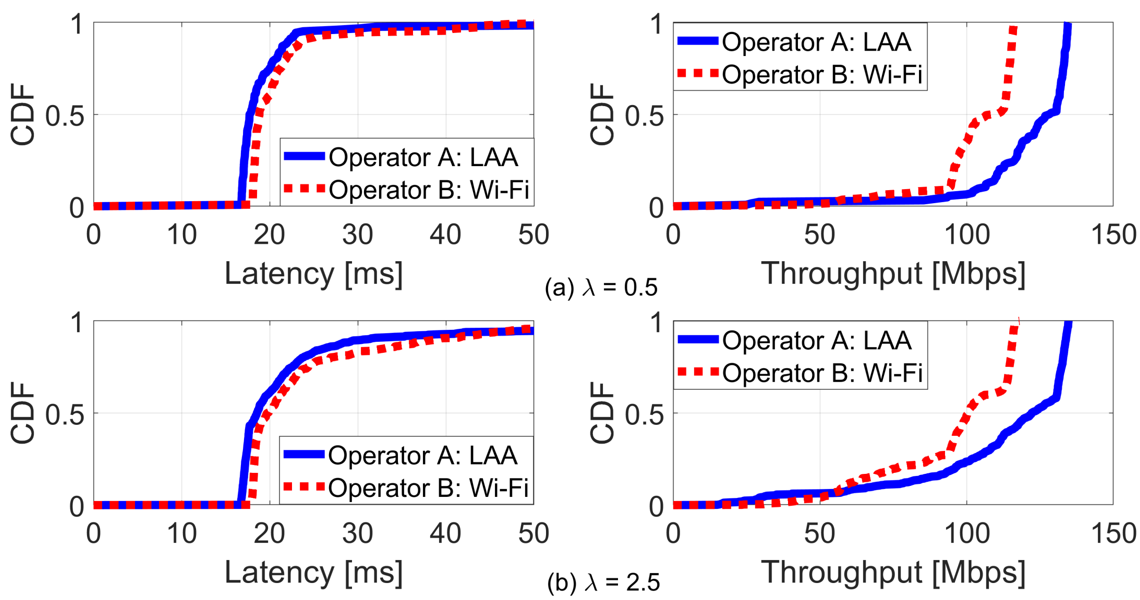


Figure 2.10: Throughputs and latencies for LAA using different traffic loads with 10 users per cell: (a) $\lambda = 0.5$ packets/second., (b) $\lambda = 2.5$ packets/second.

2.5 Summary

This chapter has discussed the coexistence mechanism for LTE networks in unlicensed frequency bands. This coexistence faces many limitations and many challenges as well, but there are many benefits that can be achieved if these limitations can be controlled. A detailed simulation study on the coexistence between LTE and Wi-Fi networks over the 5 GHz spectrum band has been carried out using the discrete event simulator ns-3 to enable the coexistence on a full protocol stack model. The obtained results demonstrate that LTE-LAA can enable a more fair coexistence (in terms of throughput and latency) than LTE-U thanks to the Category 4 LBT mechanism. The effects of changing several important parameters have been studied and the results show that the design of the LBT needs some modifications to provide more fairness for this coexistence, which will be addressed in the following chapters.

Chapter 3

Methods for the Allocation of Almost Blank Subframes for Improved LTE-U/Wi-Fi Coexistence

3.1 Introduction

In order to cope with the increased demand of wireless services and applications, LTE over unlicensed spectrum has been proposed to extend the operation of LTE to operate also over unlicensed bands. However, this extension faces various challenges regarding the coexistence between LTE-U and different technologies that use these unlicensed spectrum bands such as Wi-Fi technology. The first scenario of LTE allowing LTE to operate over unlicensed bands is Unlicensed LTE (LTE-U) duty-cycling. Specifically, LTE-U can coexist with Wi-Fi by allowing LTE-U devices to transmit only in predetermined duty cycles (DCs) or to use adaptive DCs for LTE based on the activity measurements. In this chapter, the downlink performance of LTE-U and Wi-Fi under different traffic loads is investigated. The main novelty of this work is to exploit the knowledge of the existing Wi-Fi traffic activity to select a fixed DC for LTE. Moreover, two proposed methods to allocate the blank subframes within LTE frames are provided. The Almost Blank Subframe (ABS) is proposed by 3GPP as a part of enhanced inter-cell interference coordination framework in order to combat co-channel interference in heterogeneous networks. In particular, ABS scheme allows LTE to give up some subframes in order to allow Wi-Fi transmissions. ABSs are subframes allocated for Wi-Fi with reduced DL transmission power in order not to make any interference for LTE eNBs during the silent periods [132]. However, simulation results using ns-3 simulator for LTE-U and Wi-Fi coexistence mechanism under different traffic loads are provided. In particular, the results show that the coexistence mechanism between LTE-U and Wi-Fi in the 5 GHz band achieves better total aggregated throughputs for the coexisting technologies using the proposed approach. Moreover, the location of the blank subframes plays a key role in this coexistence in terms of the total aggregated throughputs. The proposed approach exploits this feature to decide the most convenient location of blank subframes in order to improve the total aggregated throughputs. The results of this chapter have been published in [133].

The key contributions can be summarised as follows:

1) A new approach to select a fixed DC for LTE-U in coexistence with Wi-Fi technology over 5 GHz band is proposed based on the Wi-Fi activity statistics of the ON/OFF time periods.

2) Two methods to allocate the blank subframes within the LTE-U frames are proposed based on the Wi-Fi activity statistics. In Method A, the blank subframes are selected to be at the end of the DC period, while in Method B, the blank subframes are selected to be the contiguous subframes aligned with the longest Wi-Fi transmission (i.e., longest Wi-Fi ON time) within the DC period.

The rest of this chapter is organised as follows. First, Section 3.2 reviews some previous spectrum measurement methods for LTE/Wi-Fi coexsitence. In Section 3.3, a new fixed DC approach to select the LTE-U DC for a fair coexistence between LTE-U and Wi-Fi is introduced, where two methods for allocating the blank subframes for better performance are proposed. In Section 3.4, the methodology and the simulation environment are presented. In Section 3.5, the simulation results are presented and discussed. Finally, Section 3.6 summarises and concludes the chapter.

3.2 Background

Several mechanisms for spectrum sharing between LTE-U and Wi-Fi have been proposed in the literature. In [134], the coexistence between LTE-U and Wi-Fi networks over unlicensed bands has been studied and the results show that there is a trade-off between throughput and latency for this coexistence. In particular, the throughput has been affected by more than half by setting the DC for LTE-U to be 50%. In [100], LTE-U and Wi-Fi are deployed together using the carrier aggregation concept. The simulation results show that there is an improvement in the LTE-U throughput without any degradation of the Wi-Fi performance. The coexistence between LTE-U/Wi-Fi using CSAT and the coexistence between LTE-LAA/Wi-Fi using LBT mechanism are investigated in [135]. The results show that both scenarios can provide the same fairness for Wi-Fi transmissions if a suitable fair rate allocation is used. A model for the channel access probability in Wi-Fi while coexisting with LTE-U has been provided in [136]. The concept of Almost Blank Subframes (ABS) with a fixed DC in LTE-U has been used in [132] for LTE-U/Wi-Fi coexistence. The simulation results show that the ABS concept can improve the Wi-Fi throughput. In [97], a dynamic duty cycle selection technique has been introduced to give the Wi-Fi nodes more opportunities to access the channel in the unlicensed spectrum. A blank sub-frame allocation approach has been used, where some sub-frames are allocated for Wi-Fi transmissions which improves the performance of Wi-Fi and degrades the LTE performance since there is a trade-off between these technologies. On the other hand, Qualcomm [137] recommends that LTE-U uses a period of 40, 80 or 160 ms with a maximum DC of 50% where the LTE-U BSs have to observe the channel for dynamic channel selection and adaptive duty cycling. An analytical model for LTE-U/Wi-Fi coexistence with a fixed DC has been presented in [138]. The simulation results show that fairness can be achieved by tuning the DC parameter. Moreover, increasing the number of Wi-Fi nodes while LTE-U DC equals to 50% improves the throughput compared with an identical Wi-Fi network.

In general, for LTE-U/Wi-Fi coexistence, most previous work has focused on selecting pre-defined fixed DCs for LTE-U for particular network conditions and have provided the results for different settings for the LTE-U DC. Extensive studies analysing different coexistence mechanisms within the same framework with comparable results taking into account the traffic statistics for the existing Wi-Fi network are missing in the literature. In this chapter, the focus is on LTE-U with fixed duty cycling due to its design simplicity, where the DC for LTE-U is selected based on the traffic statistics of the existing Wi-Fi network. Moreover, the concept of ABS is exploited to allow the Wi-Fi transmissions at certain subframes where the highest throughput can be achieved.

Due to the increasing interest in spectrum sharing between LTE and Wi-Fi networks over unlicensed bands, various studies have been recently devoted to implement different spectrum sharing mechanisms enabling a fair coexistence between these two heterogeneous technologies. A comparison between the coexistence of LTE-U/Wi-Fi and LTE-LAA/Wi-Fi scenarios is provided in [116]. The simulation results show that coexisting LAA with Wi-Fi achieves better performance than deploying LTE-U with Wi-Fi over the unlicensed 5 GHz band. A numerical analysis is performed for LTE and Wi-Fi networks in [136]. The numerical results show that coexisting both technologies over the same unlicensed band without any modification to the existing protocols can severely degrade the Wi-Fi performance. The impact of the DC parameter on LTE-U/Wi-Fi coexistence over unlicensed bands is studied in [132] where different blank subframes are deployed within the LTE-U frame allowing Wi-Fi transmissions. The simulation results show that by deploying more blank subframes over the LTE frame, a higher Wi-Fi throughput can be achieved. In [139], an Hyper Access Point (HAP) is proposed that allows LTE-U take advantage of the Wi-Fi point coordination function protocol by dedicating a contention-free period to LTE-U users and allowing a contention period for traditional Wi-Fi users.

In general, deploying LTE with Wi-Fi over unlicensed bands is called LTE-U duty-cycling where transmissions are managed by the ON/OFF time periods. Moreover, it is worth mentioning that the LTE-U Forum specifications [118] provide limits for the ON/OFF durations. Specifically, the maximum ON duration is 20 ms and the minimum ON duration is 4 ms, while the minimum OFF duration is 1 ms, leading to a maximum DC of 95%. Moreover, LTE-U employs an adaptive DC mechanism based on the CSAT algorithm, i.e., it adapts and changes its DC based on the channel activity measurements.

Overall, LTE-U has key advantages such as the fact that it relies on mechanisms provided by the legacy 3GPP specifications, thus removing the need of significant changes for the LTE specification, it is suitable where there are free channels to increase the capacity and it is not complex to be implemented. Therefore, to enhance the performance for LTE-U/Wi-Fi coexistence, a new approach with a fixed DC for LTE-U is here proposed. In addition, two methods for ABS allocation based on the Wi-Fi activity statistics are proposed in this chapter as well.

3.3 The proposed approach and methods

The current LTE-U employs an adaptive DC based on the medium activity measurements (i.e., its DC is dynamic). This may degrade the total aggregated throughputs for the coexisting networks since both networks have to change their DCs proportionally. On the other hand, the ON/OFF activity statistics of the existing Wi-Fi network could be

Table 3.1: The Duty Cycles for Wi-Fi and LTE-U under different traffic loads.

	λ (packets/second)		
	0.5	**1.0**	**1.5**
DC_{Wi-Fi}	0.05	0.10	0.125
DC_{LTE-U}	0.95	0.90	0.875

exploited to set a static DC for LTE-U. In particular, the Wi-Fi activity statistics can be estimated by the LTE-U network based on energy detection. In particular, the DC can be calculated using two approaches. Firstly, the DC can be calculated as the ratio between the sensing events where the decision is ON divided by the total number of sensing events. This means that the channel is sensed periodically to check if it is ON or OFF. On the other hand, another approach can be followed to calculate the DC is based on the mean busy and the mean idle periods and the DC is calculated as the ratio between the mean busy periods divided by the total periods (i.e., mean busy and mean idle periods). These approaches are described in detail in [140]. However, LTE-U can compute the DC for the existing Wi-Fi network after observing the channel for a sufficient long time. This sufficent time depends on the particular operating conditions and can be determined based on the results provided in [141] which investigates for how long the channel needs to be observed in order to estimate the different statistics with a given level of accuracy. Then, the DC for LTE-U can be set as follows

$$DC_{LTE-U} = 1 - DC_{Wi-Fi} \tag{3.1}$$

Instead of updating the DC for LTE-U (i.e., DC_{LTE-U}) based on the activity statistics, DC_{LTE-U} will be kept static. The procedure is illustrated in Table 3.1, which shows the DCs for Wi-Fi and LTE-U estimated by the LTE-U network for different traffic loads in terms of the number of packets per second (λ). This approach describes the proposed DC setting strategy for LTE-U.

Qualcomm recommends that LTE-U uses a period of 40, 80, or 160 ms [137]. In this work, a 40 ms DC period is considered, which is divided into forty 1-ms subframes. The decision of LTE-U to transmit or not in each of these subframes can be represented with a vector of 40 bits, except for subframes 0 and 35, which are reserved for the Master Information Block (MIB) and the System Information Block 1 (SIB1), respectively. This approach allows for several DC settings for LTE-U strategies. In this work, the following

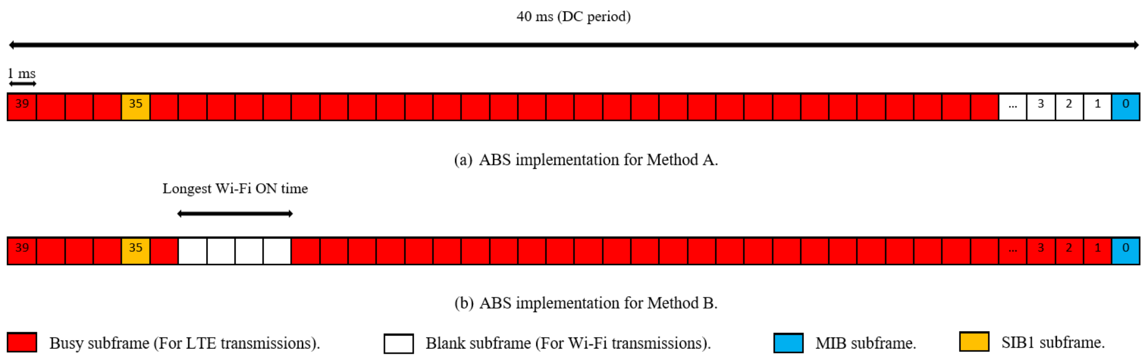


Figure 3.1: The ABS pattern for the proposed methods for $\lambda = 1.0$ packets/second.

two methods to allocate the blank subframes are considered:

Method A

This method defines the location of the adequate number of blank subframes to be selected within the LTE-U frame. The number of blank subframes are selected based on the Wi-Fi activity statistics as shown in equation (3.1). In addition, the blank subframes are selected to be at the end of the duty cycle period as illustrated in Fig. 3.1a.

Method B

This method is similar to Method A but defines different location for the blank subframes within the LTE-U frame. In particular, the blank subframes are selected to be contiguous subframes aligned with the longest Wi-Fi transmission within the DC period. The motivation for this method is to hopefully achieve better total aggregated throughputs for the existing networks because the blank subframes are allocated alongside the longest Wi-Fi transmission time leading to less collisions between the coexisting networks. Fig. 3.1b illustrates the ABS implementation for this method.

3.4 Methodology and Simulation Setup

The coexistence performance for LTE-U and Wi-Fi is evaluated following the current LTE-U simulation conditions except the updating strategy for DC_{LTE-U}, where the proposed fixed DC for LTE-U strategy is implemented. In this work, the performance for LTE-U and Wi-Fi networks has been evaluated using ns-3. In particular, an indoor scenario is considered with two operators; operator A (Wi-Fi) and operator B (LTE-U) using the same 20 MHz channel over the 5 GHz band. Fig. 2.2 describes the implementation for the LTE-U/Wi-Fi indoor scenario. Each operator deploys 4 eNodeB (eNBs)/Access Points (APs) and they are equally spaced. 20 User Equipments (UEs)/Stations (STAs) are randomly distributed for each operator. All the nodes (i.e., eNBs/APs/UEs/STAs) are equipped with two antennas for 2x2 MIMO scheme. In addition, the Wi-Fi nodes detect each other at -62 dBm but they detect the LTE-U nodes at -82 dBm. On the other hand, LTE-U nodes detect the Wi-Fi nodes at -72 dBm. Moreover, the employed traffic model simulates file transfers arriving according to a Poisson process with arrival rate λ . The File Transfer Protocol (FTP) has been implemented to operate over User Datagram Protocol (UDP). A file size of 0.5 MB is considered with various recommended arrival rates ($\lambda = 0.5, 1.0, 1.5$ packets/second) with simulation duration of 240 seconds [96]. The simulation scenario details are provided in Table 3.2.

In order to estimate the activity statistics for the existing Wi-Fi network, two Wi-Fi networks are deployed together. In this scenario, the DC for the existing Wi-Fi network can be estimated. The DC for LTE-U (i.e., DC_{LTE-U}) can then be evaluated and set based on equation (3.1). Finally, one of the Wi-Fi networks is replaced by an LTE-U network for final simulations, allowing LTE-U/Wi-Fi coexistence and assessing the validity of the proposed methods.

3.5 Simulation Results

The performance of LTE-U and Wi-Fi networks is investigated in this section using the proposed approach to set the DC for LTE-U (i.e., DC_{LTE-U}) and using the proposed methods to allocate the blank subframes based on the Wi-Fi activity statistics. The individual throughputs for Wi-Fi and LTE-U networks are provideded as well as the total aggregated throughputs for both networks. Moreover, the LTE-U latency using the proposed methods is also provided.

In Fig. 3.2, the throughputs for Wi-Fi, LTE-U and the total aggregated throughputs for different DC_{LTE-U} at $\lambda = 0.5$ packets/second using the proposed approach (i.e., using equation (3.1)) and method A are presented. It can be seen that as the DC_{LTE-U} increases, the Wi-Fi throughput decreases due to allocating less blank subframes for Wi-Fi transmissions. On the other hand, the LTE-U throughput increases as the DC_{LTE-U} increases since it allows more subframes for LTE-U to transmit its own data. In general, it

Table 3.2: Deployment scenario and simulation parameters

Parameter	**Value or description**
Network layout	Indoor scenario
System bandwidth	20 MHz
Carrier frequency	5 GHz
Total BS Tx power	18 dBm
Total UE Tx power	18 dBm
Propagation loss model	ITU Indoor/Hotspot
Antenna pattern	2D omni-D
BS antenna gain	5 dBi
UE antenna gain	0 dBi
UE noise figure	9 dB
ABS pattern duration	$40ms$
Tx Opportunity (TxOP)	$8ms$
Slot duration	$9\mu s$
UE dropping	Randomly
Traffic model	FTP model 1

is observed that the maximum aggregated throughput for both networks can be achieved at $DC_{LTE-U} = 0.95$. Thus, coexisting LTE-U with Wi-Fi using DC_{LTE-U} set to be 0.95 for $\lambda = 0.5$ achieves the highest total aggregated throughput for the coexisting networks, which is obtained by maximising the LTE-U throughput at the expense of a lower Wi-Fi throughput. Thus, instead of updating the DC_{LTE-U}, a fixed DC_{LTE-U} at certain value can achieve the best total aggregated throughput. In addition, the proposed approach to set the DC_{LTE-U} based on the existing Wi-Fi activity statistics provides the best total aggregated throughput compared to other static arbitrary DCs for LTE-U. It is worth noting that this particular configuration might not be suitable in scenarios where the Wi-Fi and LTE-U networks are managed by different operators and the Wi-Fi operator needs to preserve its network data rates, but may be of practical interest in scenarios where a mobile operator has Wi-Fi access points co-located with LTE femtocells and the main objective is to maximise the total aggregated throughput of the whole network infrastructure, including together both networks (assuming that their customers can connect to either network in order to gain data connectivity).

Fig. 3.3 presents the Wi-Fi throughputs for the existing Wi-Fi network for the reference case (i.e., Wi-Fi and Wi-Fi coexistence) and the two methods considered, under different traffic loads. It can be seen that coexisting LTE-U with Wi-Fi impacts the existing Wi-Fi

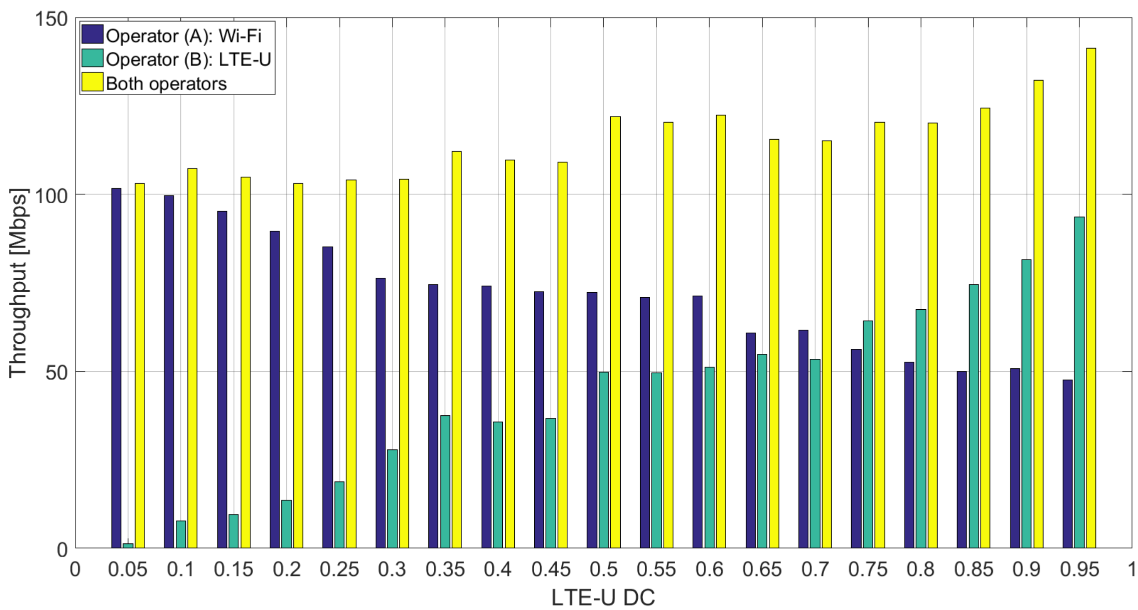


Figure 3.2: Throughputs for 95% of users for both coexisting operators using different DCs for LTE-U.

throughput compared to the reference case. Concretely, the Wi-Fi network experiences a slight throughput degradation as a result of introducing the LTE-U network, however the LTE-U network is able to achieve a throughput higher than the amount by which the Wi-Fi throughput is reduced, which leads to a higher aggregated throughput as explained earlier. Moreover, it can be seen that both proposed methods achieve a comparable performance in terms of Wi-Fi throughput. The LTE-U throughputs for the two proposed methods (i.e., Method A and Method B) considered with different traffic loads are depicted in Fig. 3.4. In this case, it can be observed that Method B achieves better LTE-U throughput performance compared to Method A. A throughput performance improvement of 10% (9.4 Mbps), 6% (5.1 Mbps) and 5.5% (3.8 Mbps) is observed for $\lambda = 0.5$, 1.0 and 1.5 packets/second, respectively. These results indicate that a smart allocation of the blank subframes based on the Wi-Fi traffic patterns can improve the LTE-U throughput without any impact at all on the Wi-Fi throughput performance.

Fig. 3.5 reperesents the LTE-U latencies for the two proposed methods under different traffic loads. It can be noticed that both methods achieve a comparable performance in terms of latency.

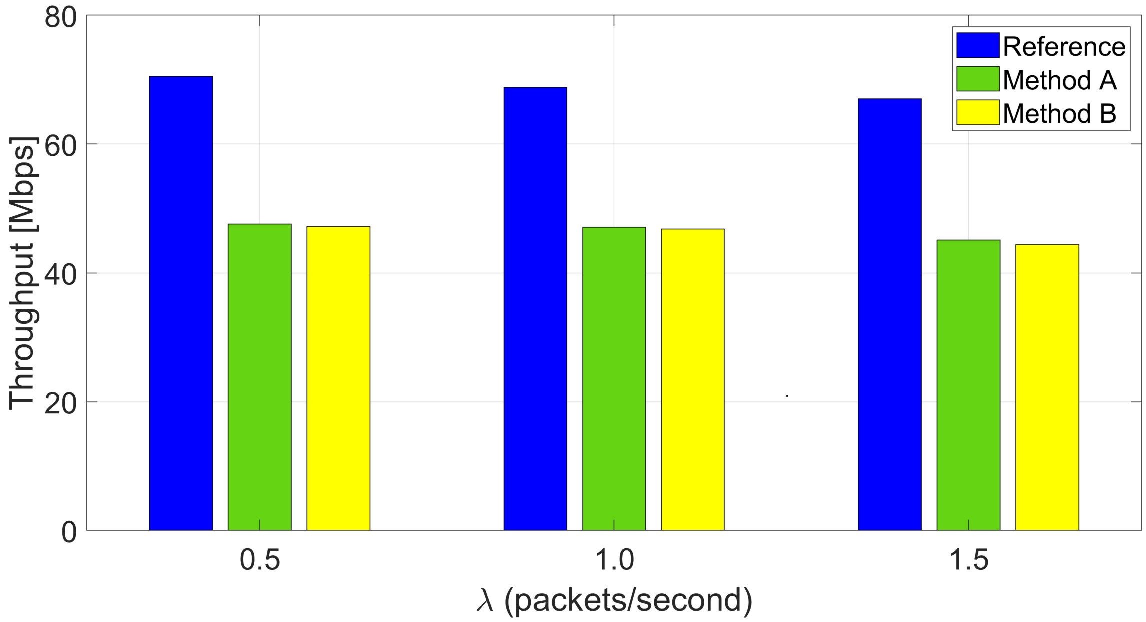


Figure 3.3: Operator (A): Wi-Fi throughputs for 95% of users using different methods under different traffic loads.

Finally, the total aggregated throughputs for both networks (i.e., LTE-U and Wi-Fi) are depicted in Fig. 3.6. It can be seen that Method B provides better total aggregated throughputs compared with Method A. The performance improvement is 6.4% (9 Mbps), 3.7% (4.8 Mbps) and 2.7% (3.1 Mbps) for λ = 0.5, 1.0 and 1.5 packets/second, respectively. This improvement is due to the blank subframes in Method B being selected to be contiguous aligned with the longest Wi-Fi transmission within the DC period. It is worth highlighting that these performance improvements are obtained at no cost at all.

3.6 Summary

The current LTE-U employs an adaptive DC for coexisting with Wi-Fi over unlicensed spectrum bands. This approach does not achieve the best performance in terms of total aggregated throughput of the coexisting technologies. A novel and simple approach with fixed DC for LTE-U has been proposed in this chapter to select the DC for LTE-U based on the knowledge of Wi-Fi traffic activities to achieve a better performance for the coexisting technologies. Moreover, two methods that define the location of the adequate number of

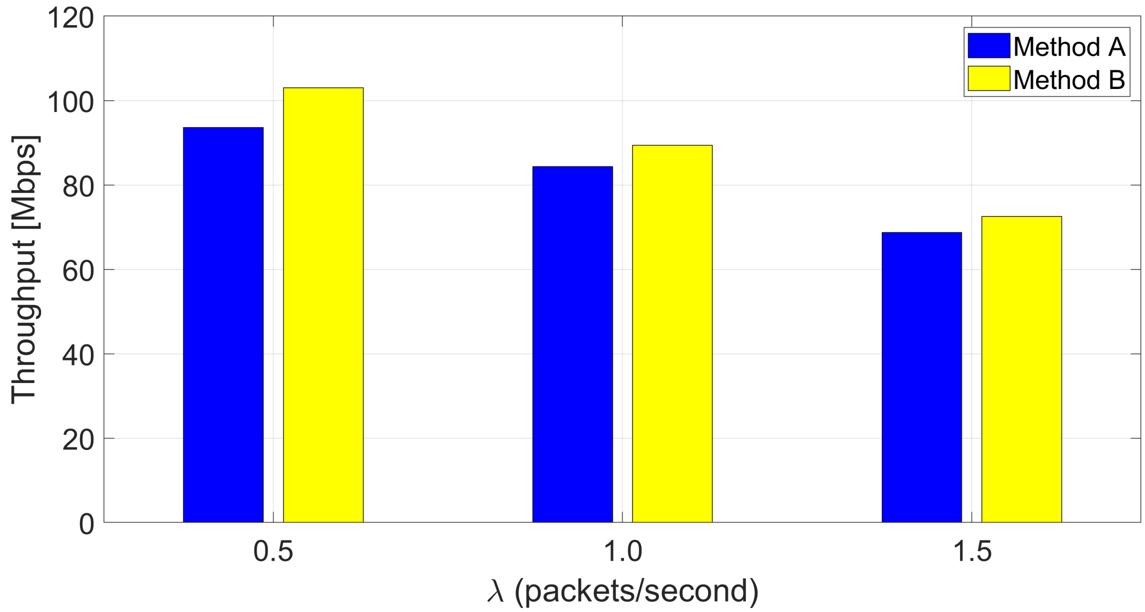


Figure 3.4: Operator (B): LTE-U throughputs for 95% of users using different methods under different traffic loads.

blank subframes to be selected within the LTE-U frame have been proposed. The obtained simulation results show that the proposed methods can achieve a significant improvement in the LTE-U throughput without any impact on the Wi-Fi throughput, thus enhancing the capacity available to LTE-U at no cost.

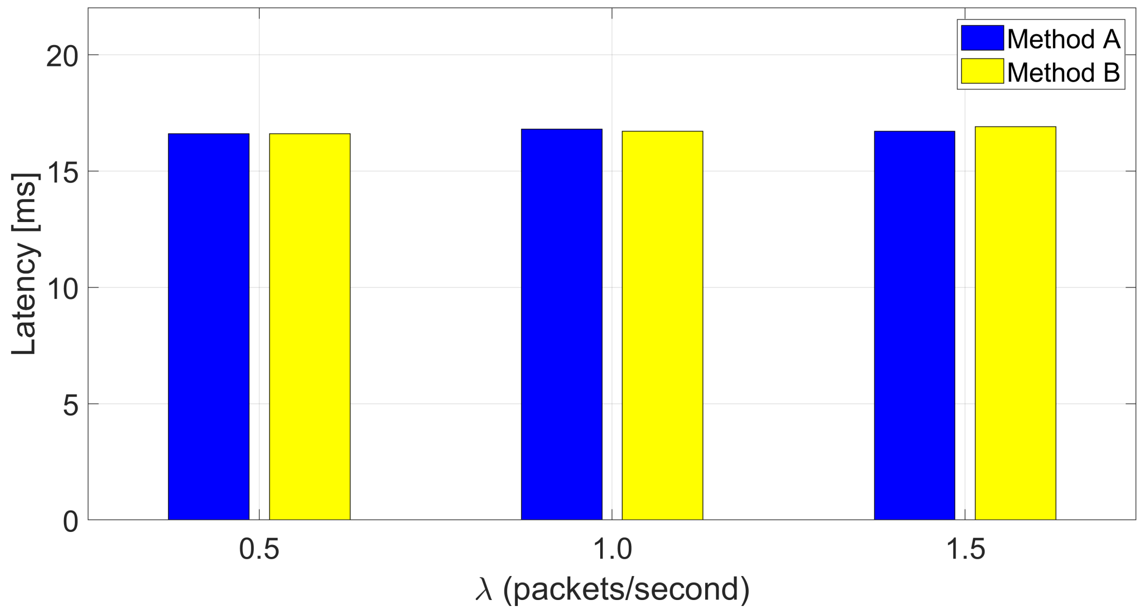


Figure 3.5: Operator (B): LTE-U latencies for 95% of users using different methods under different traffic loads.

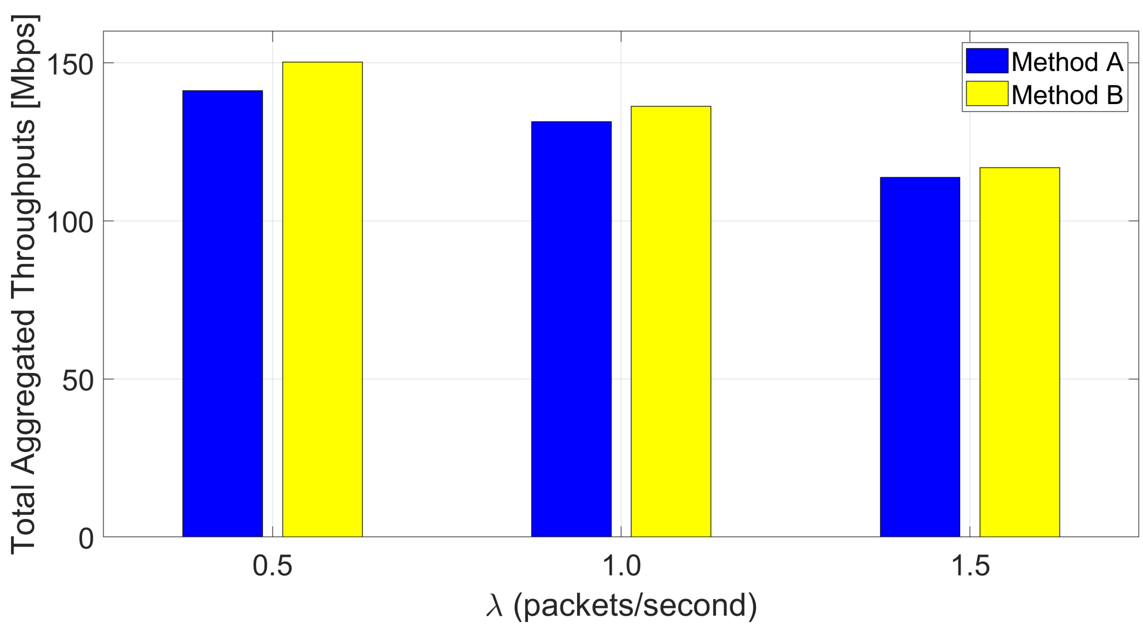


Figure 3.6: Total aggregated throughputs for 95% of users for both operators using different methods under different traffic loads.

Chapter 4

Methods for the Adaptation of Waiting and Transmission Times in LTE-LAA

4.1 Introduction

Long Term Evolution-Licensed Assisted Access (LTE-LAA) has been pointed out as a key solution to cope with the increasing amounts of data traffic and the scarcity of the licensed spectrum. The 3GPP has standardised LAA to operate over the 5 GHz unlicensed spectrum which is mainly occupied by Wi-Fi. It is a challenging problem to ensure a fair coexistence between these technologies. Several studies have been proposed in the literature to allow a fair LAA/Wi-Fi coexistence. In this chapter, various methods are proposed to adapt/select the waiting times for LAA based on the activity statistics of the existing Wi-Fi network. The main novelty is that the knowledge of the existing Wi-Fi activities is exploited to tune the boundaries of the Contention Window (CW) for LAA and to select the waiting times for LAA. Moreover, a dynamic method is proposed to adapt the Transmission Opportunity (TxOP) times for LAA based on the Hybrid Automatic Repeat Request (HARQ) feedbacks. The methods are evaluated using ns-3 network simulator based on the 3GPP fairness definition. The results show that selecting fixed waiting times for LAA based on the existing Wi-Fi activities is more friendly to the existing Wi-Fi and provides better total aggregated throughputs for both coexisting networks compared to the 3GPP Category 4 Listen Before Talk (Cat 4 LBT) algorithm. Moreover, the proposed dynamic TxOP method is more friendly to the existing Wi-Fi and provides better total aggregated throughputs compared to the fixed TxOP period approach of the 3GPP Cat 4 LBT scheme.

The remainder of this chapter is organised as follows. First, some related works for LAA/Wi-Fi coexistence mechanisms are presented in Section 4.2. The contributions are provided in Section 4.3. The 3GPP Category 4 (Cat 4) LBT algorithm is introduced in Section 4.4. Various methods are presented in Section 4.5 to adapt/select the waiting times for LAA. Section 4.6 presents a dynamic approach to configure the transmission times for LAA. The considered methodology, simulation environment and used model are described in Section 4.7. Section 4.8 presents and analyses the obtained simulation results. Finally, the conclusions are summarised in Section 4.9.

4.2 Previous Related Work

The fairness of LTE-LAA/Wi-Fi coexistence has been widely studied in the literature [142]. In [143], a listen-before-talk access mechanism featuring an adaptive distributed control function protocol is proposed, whereby the backoff window size is adaptively adjusted according to the available licensed spectrum bandwidth and the Wi-Fi traffic load to satisfy the quality-of-service requirements of small cell users and minimise the collision probability of Wi-Fi users. An LTE-LAA module has been developed for ns-3 network simulator in [144] to investigate the performance of LTE-LAA/Wi-Fi coexistence scenario. The simulation results show that the fairness depends on the design parameters of the LBT algorithm for LAA. The work reported in [106] indicated that the transmission times of LTE eNB should be fixed at the beginning of the Distributed coordination function Inter-frame Space (DIFS) of Wi-Fi AP and the CCA period of LTE eNB should be shorter than DIFS period leading to no collisions between LTE and Wi-Fi networks. In [132] and [145], an LTE muting scheme is considered where LTE eNBs follow a predetermined muting pattern allowing the transmission of LTE nodes. The impact of the LBT design parameters for LTE-LAA/Wi-Fi coexistence is investigated in [146]. In particular, an alternative approach to increase the LAA Contention Window (CW) is proposed based on the observed number of free slots during a specific time interval. The results show that the standard algorithm outperforms the proposed one. An adaptive LBT scheme for LAA based on Markov chain model is proposed in [147]. Specifically, a partially-randomised initial CCA (iCCA) scheme and an adaptive CW size scheme are considered for the LBT algorithm of LAA based on the detection by the LAA system. The simulation results show that the proposed strategy is effective for LAA to achieve the fairness in the downlink scenario for LAA/Wi-Fi coexistence. In [121], two LBT algorithms have been proposed. One of them is asynchronous LBT based on the Distributed Coordination Function (DCF) protocol since it uses the Request-To-Send/Clear-To-Send (RTS/CTS) signals to check the availability of the channel. The other one is synchronous LBT, where the data subframes are synchronized with the licensed LTE carrier. Thus, the second algorithm needs some changes in the LTE specification. A CW size adjusting method within an enhanced LBT algorithm of LAA is proposed in [148]. The CW size is adjusted based on the exchanged information from the neighbor nodes of the considered scenario. The simulation results show that the proposed scheme achieves better performance compared to the fixed scheme of LBT for the various coexistence scenarios. In [149], a fair downlink traffic management scheme is proposed for LAA/Wi-Fi networks to tune the minimum CW values and to assign feasible weights for LAA eNBs under different traffic loads. The simulation results show that the proposed scheme improves the aggregated utility of LAA/Wi-Fi networks but the Wi-Fi throughput decreases slightly compared to the static approach of minimum CW configuration. In [150], a CW adjustment method is proposed based on a simple gradient approach enabling a fair coexistence between LTE-LAA and Wi-Fi networks but the authors did not provide an analytical throughput model for the proposed method. An adaptive LBT algorithm is proposed in [151] where the different design parameters of LBT are adapted dynamically based on the varying traffic load and the CW size of the existing Wi-Fi system. In [152], a modified model to investigate the Energy Detection (ED) threshold of LAA is proposed. The numerical and experimental results show that the fairness between LTE-LAA and Wi-Fi networks depends on the channel access parameters such as ED threshold and Transmission Opportunity (TxOP) period of LAA. In [153], the fundamental trade-off between co-channel interference and collision probability is investigated and addressed by means of a power allocation rule with double water-filling lines, which achieves the complete set of Pareto optimal solution by means of the weighted Tchebycheff method. In [154], a joint licensed and unlicensed resource block allocation scheme is proposed to maximise the energy efficiency of LAA taking into account fair resource sharing between LTE and Wi-Fi networks. In [155], an adaptive p-persistent channel access scheme for LAA (named p-LAA protocol) is proposed to balance the trade-off between throughput and fairness for the coexistence network. A Q-learning algorithm is proposed in [156] to adjust the

TxOP periods for Wi-Fi and LAA based on the current traffic load or expected capacity. The simulation results show that the proposed algorithm can achieve fairness while maintaining high throughput when the algorithm is applied. The work presented in [157] provides a Markov chain model analysis for LAA/Wi-Fi coexistence scenario where the data are transmitted in a single transmission opportunity backoff. The numerical results show that the proposed model provides better performance for Wi-Fi network and for LAA networks in dense deployments. Overall, the various proposed coexistence mechanisms do not perfectly match the fairness definition as described by 3GPP TR 36.889. Moreover, taking into account the activity statistics of the existing Wi-Fi network for any proposed coexistence mechanism is missing in the literature. In particular, most of the studies in the literature aim to maximise the LTE throughput while other studies do not achieve fairness. Moreover, exploiting the knowledge of the existing Wi-Fi statistics to achieve a fair coexistence mechanism is missing in the literature.

4.3 Contributions

In this chapter, the focus is on LTE-LAA given that it represents the most promising unlicensed LTE approach to achieve fairness between LTE and Wi-Fi networks because it is generally more fair to Wi-Fi compared to LTE-U. Current studies mostly focus on the design of mechanisms that enable a fair coexistence between LTE-LAA and Wi-Fi over unlicensed bands. Considering the latest LBT algorithm of 3GPP, Category 4 (Cat 4) LBT algorithm, it can be noticed that the coexistence performance of LTE-LAA/Wi-Fi over the unlicensed 5 GHz band does not perfectly match the fairness definition as described by 3GPP TR 36.889 [96], as it was shown in the results reported in [116]. Specifically, a Wi-Fi performance degradation can be noticed due to this heterogeneous coexistence between LTE-LAA and Wi-Fi networks. This degradation is due to some potential drawbacks of the 3GPP Cat 4 LBT algorithm which are described in Section 4.4 and that are addressed and overcome by the methods proposed in this chapter. The main novelty of the methods proposed and analysed in this chapter is the exploitation of the activity statistics of the Wi-Fi network for an adequate configuration and operation of the LTE-LAA method. As opposed to previous related work, where the activity statistics of the Wi-Fi network are not taken into account, the methods proposed in this chapter exploit the availability of this information in order to optimise the performance not only of LTE-LAA but also of the Wi-Fi network itself.

The main contributions of this chapter are as follows:

1. Two dynamic CW methods for LAA are proposed to improve the performance of LAA/Wi-Fi coexistence based on the 3GPP fairness definition. In particular, the activity statistics of the existing Wi-Fi network are exploited to set the upper bounds of the LAA CW, as opposed to the 3GPP Cat 4 LBT method, which considers a limited set of fixed upper bounds for the LAA CW. The results have been published in [158, 159].

2. Unlike the 3GPP Cat 4 LBT algorithm which considers a dynamic CW scheme based on the Hybrid Automatic Repeat Request (HARQ) reports to adapt the upper bound of the LAA CW, a static CW method for LAA is proposed where the activity statistics of the existing Wi-Fi network are exploited to select a single fixed upper bound for the LAA CW instead of using variable upper bounds for the LAA CW size. The results have been published in [159, 160].

3. A fixed waiting time method for LAA is proposed where the activity statistics of the Wi-Fi network are used to set fixed waiting times for LAA before transmission instead of following a CW-based approach. The results have been published in [159].

4. Various variants are proposed to select the lower bound of the CW of LAA based on the minimum and mode of the activity statistics of the existing Wi-Fi network. Moreover, a fixed waiting time method for LAA is proposed based on these variants as well. The results have been published in [159].

5. A novel dynamic TxOP period approach is proposed where the observed Wi-Fi transmission pattern is exploited to configure the maximum TxOP length for LAA using a dynamic scheme. The results have been published in [159, 161].

4.4 Category 4 (Cat 4) LBT in LTE-LAA

The licensed LTE MAC protocol has no frame for collision detection and this is the key difference between LTE and Wi-Fi technologies. This requires a modification for the LTE air interface in order to include an LBT algorithm within the LTE MAC. Coexisting LTE with Wi-Fi over the same unlicensed band without any fair mechanism can degrade the Wi-Fi performance given the lack of an LBT mechanism in LTE (since it was designed assuming exclusive access to the spectrum) and the fact that Wi-Fi nodes would frequently sense the channel as busy before attempting any transmission, thus preventing their access to the channel. As a result, an LBT algorithm for LAA was introduced in 3GPP Release 13, which is referred to as Category 4 (Cat 4) LBT [96,162]. A general overview of LAA is provided in section 1.1.7 while this section provides the technical details of the coexistence algorithm that are relevant to the work presented in this chapter.

The 3GPP Cat 4 LBT algorithm is similar to the Wi-Fi DCF protocol as it can be seen in Fig. 4.1. In this algorithm, a CCA period is considered to check the availability of the channel before transmission. In particular, an LAA eNB is allowed to transmit its own data after sensing the channel to be free for an initial CCA (iCCA) period (e.g., 34μs); otherwise, the extended CCA (eCCA) stage starts. During the eCCA stage, a backoff process starts by selecting a random number $N \in [0, q-1]$, where N indicates the number of idle slots that need to be observed before transmission, while $q-1$ represents the upper bound of the CW, which varies according to an exponential backoff. In particular, the channel is observed by LAA eNB for a time equal to N multiplied by the CCA slot time period (e.g., 9μs). When the channel is free, another eCCA period (e.g., 9μs) begins and N is decreased by one if the channel is clear. When N decrements to zero, the LAA eNB starts the transmission for a fixed configurable Transmission Opportunity (TxOP) time, which can be up to 10 ms depending on the channel access priority class (see Table 4.1 and [162, Table 15.1.1-1] for details). If the LAA eNB needs another transmission, the eCCA stage is repeated again. However, the value of N is related to the channel access priority class which categorises the traffic type. In particular, the CW size $q-1$ is initialised with CW_{min} and it is exponentially increased based on Hybrid Automatic Repeat Request (HARQ) feedbacks. Table 4.1 provides the values of CW_{min} and CW_{max} for each channel access priority class. For example, for the priority class 3, the initial value of the upper bound of the CW, $q-1$, is 15 and it is updated to 31 by doubling q if 80% of HARQ feedbacks from the first subframe of the latest transmission are Negative Acknowledgments (NACKs). The upper bound of the CW $q-1$ is again updated to 63 if another 80% of HARQ feedbacks are NACKs. Otherwise, the upper bound of the CW $q-1$ is reset to the initial value (i.e., 15). Thus, the upper bound of the LAA CW $q-1$ for class 3 varies between $\{15, 31, 63\}$.

There are a few drawbacks of the 3GPP Cat 4 algorithm which considers the HARQ feedbacks to update the LAA CW [163,164]. In particular, the LAA CW size will not be updated if less than 80% of the users suffer from the collision since the collision remains

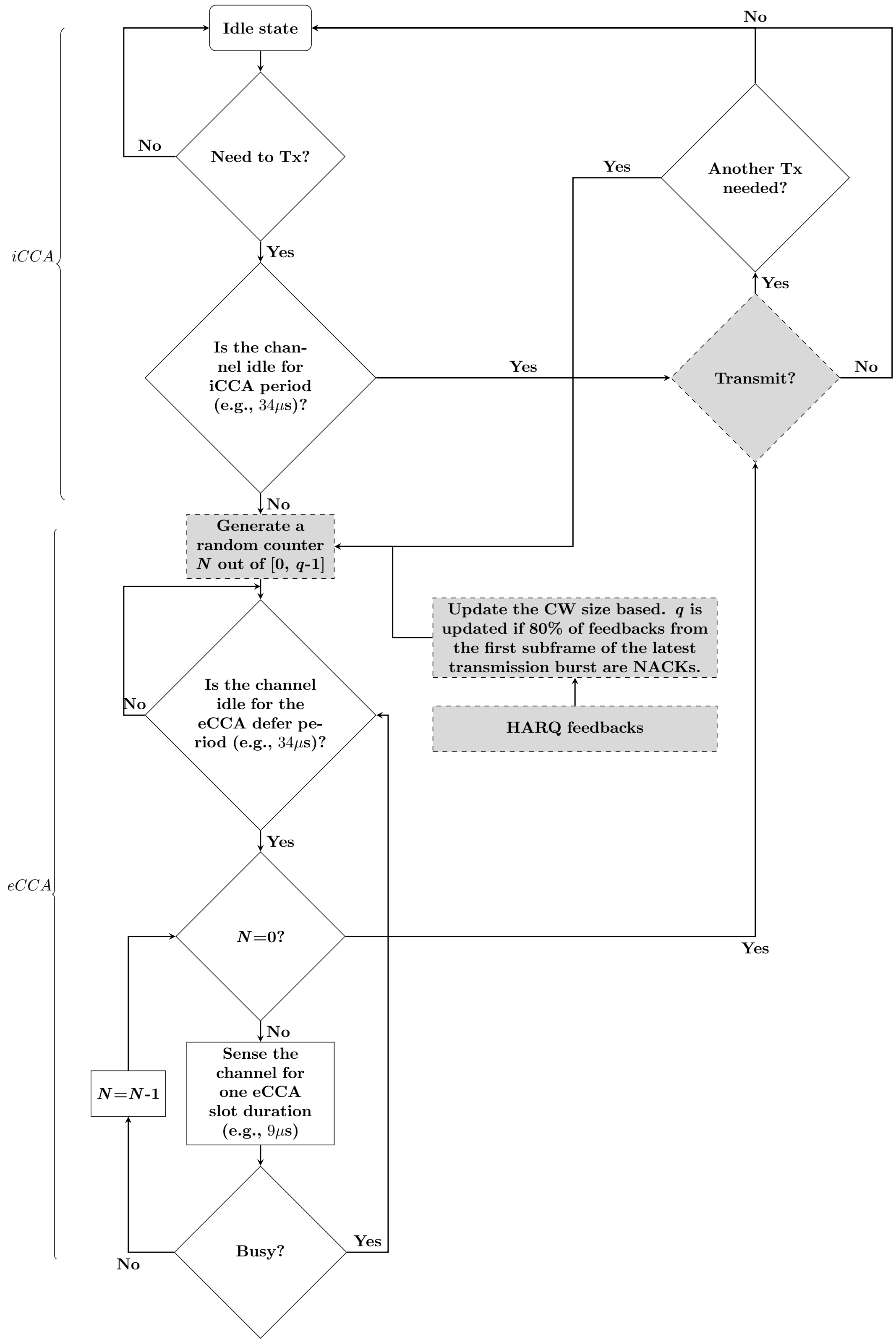


Figure 4.1: 3GPP Cat 4 LBT algorithm [96].

Table 4.1: Channel access priority classes for LAA [162].

Channel access priority class	$\mathbf{CW_{min}}$	$\mathbf{CW_{max}}$	**TxOP**
1	3	7	2 ms
2	7	15	3 ms
3	15	63	8/10 ms
4	15	1023	8/10 ms

undetected below this threshold. Moreover, the algorithm only considers the detection of the first subframe of the transmission to update the CW size but the collisions from other subframes are neglected. Furthermore, the performance of LAA/Wi-Fi coexistence is affected by the configuration of the LBT parameters such as the CW and the TxOP length of LAA [124, 151, 165]. However, it can be noted that the adaptation approach of the LAA CW in the standard Cat 4 LBT algorithm does not take into account the activity statistics of the existing technology (i.e., Wi-Fi) and it configures the upper bound of the LAA CW to be 15, 31 or 63 (for class 3) regardless of the existing Wi-Fi activity patterns. Moreover, the Cat 4 LBT algorithm allows LAA eNBs to transmit, after the channel availability check, for a fixed TxOP period. It can be noted that this static TxOP approach is not the most efficient approach for a fair coexistence between LAA and Wi-Fi networks where the LAA TxOP length is kept fixed for all transmissions regardless of the HARQ feedbacks. Therefore, to enhance the performance of the current Cat 4 LBT algorithm, different methods are proposed in this chapter to update/select the LAA CW boundaries. The dashed shaded boxes in Fig. 4.1 highlight the procedure of the standard Cat 4 LBT that will be modified to include these proposed methods. In addition, a novel method is proposed to configure the TxOP length in a dynamic manner which will be included instead of the dashed shaded diamond in Fig. 4.1. All these methods are described in the following sections.

4.5 Methods to Adapt LTE Waiting Times

In this section, various methods are presented to adapt/select the lower and upper bounds of the LAA CW, which determine the waiting times of LTE-LAA, based on the Wi-Fi activity statistics. In addition, various methods are described to select fixed waiting times for LAA eNB.

4.5.1 Dynamic CW (DynCW) Methods

As stated before, the standard 3GPP Cat 4 LBT algorithm follows a similar contention mechanism to that of Wi-Fi technology aiming to achieve a fair coexistence between LTE-LAA and Wi-Fi networks. In specific, LAA updates the upper bound of the CW, $q-1$, by doubling q from 15 to 31 and to 63 based on the HARQ feedbacks when the channel is sensed to be busy. It is worth noting that this increase in the upper bound of the LAA CW is heuristic and ignores the actual ON/OFF activities of the existing Wi-Fi network which may lead to an inefficient spectrum utilisation. In particular, if the channel is sensed to be busy by the LAA eNB, the upper bound of the CW is doubled, which in many cases may lead to longer waiting times than the actual occupancy times of the Wi-Fi transmissions, then LAA would wait a long time before re-accessing a channel that could actually be empty since a long time ago. This behavior would degrade the LAA performance by increasing latencies and reducing throughputs for LAA. As a result, considering the activity statistics of the existing technology (i.e., Wi-Fi) should provide a more efficient channel access mechanism since the LAA waiting times would be aligned with the actual occupancy times of the Wi-Fi network, thus reducing the latency and increasing the throughput for LAA. Two adaptation methods for the upper bound of the CW of LAA, $q-1$, are proposed here based on the activity statistics of the existing Wi-Fi network [158].

It is worth mentioning that the existing Wi-Fi activity statistics can be estimated by the LTE system without any coordination between the coexisting networks and this can be performed based on the energy detection sensing decisions of the LAA algorithm [91,140,166]. In particular, LAA eNB can periodically sense the Wi-Fi channel state when LAA is not transmitting to estimate the Wi-Fi ON time periods. After observing the ON Wi-Fi channel state for a sufficient large number of ON periods, the LAA network can compute the Cumulative Distribution Function (CDF) for the ON time periods of the existing Wi-Fi network. This CDF, which describes the activity pattern of the existing Wi-Fi network, can be exploited to adapt the upper bound of the CW of LAA in an efficient manner instead of following the standard adaptation method as specified by the 3GPP Cat 4 LBT algorithm which doubles the q value regardless of the activity statistics of the existing Wi-Fi network.

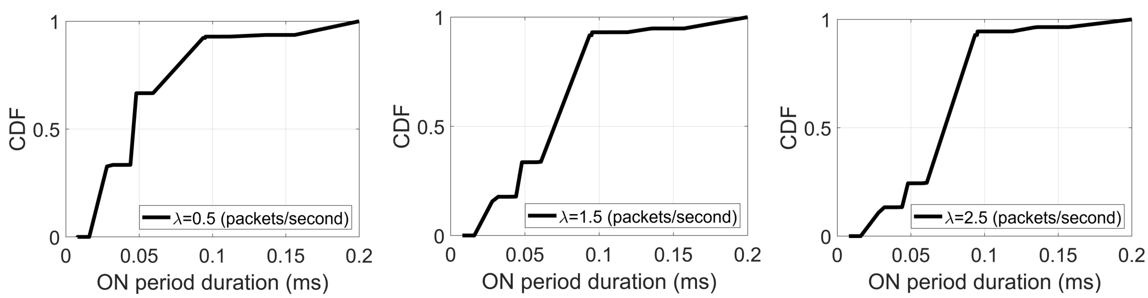


Figure 4.2: CDFs of the ON Wi-Fi times under different traffic loads and a packet size of 0.5 MB (this is the packet size at the application layer, see Section 4.7).

To illustrate the proposed method, Fig. 4.2 shows the CDFs of the Wi-Fi ON times estimated by the LTE network. In addition, Table 4.2 provides the corresponding values of the upper bound of the LAA CW, $q-1$, for different percentile points of the CDFs under different traffic loads. Fig. 4.2 is used to compute the values in Table 4.2 by dividing the ON times of each percentile point by the LAA slot duration (9 μs) and rounding the result to the nearest integer toward infinity (i.e., ceil function). For example, for $\lambda =$ 1.5 packets/second, the 50% percentile point corresponds to a Wi-Fi ON time of around 70 μs, which divided by 9 μs and ceiled results in the value $q-1=8$ shown in Table 4.2 for the 50% percentile and $\lambda = 1.5$ packets/second. All the provided values in Table 4.2 are calculated following the same procedure. It is worth mentioning that a percentile point of 100% in a theoretical CDF model is not feasible generally since the corresponding ON time would tend to infinity. However, the CDF that is used by LAA for the CW adaptation is based on empirical observations of Wi-Fi ON times, which necessarily have a finite maximum and this value is selected as the 100% percentile point. This approach allows various adaptation methods. Two dynamic adaptation methods for the LAA CW are discussed below.

Notice that the CDF of the Wi-Fi ON times will be affected not only by the packet inter-arrival times as illustrated in Fig. 4.2 but also by other network conditions such as the number of Wi-Fi APs, LTE-LAA eNBs and total number of users. If any of these network conditions change, the CDF of the Wi-Fi ON times will change as well. However, the LTE-LAA system will not be required to have any prior knowledge of these conditions. Note that the estimation of the required CDF and the resulting percentile points can be implemented as an online, real-time learning process. Any changes in the network conditions will automatically result in a change in the estimated CDF and the resulting

Table 4.2: Upper bound CW values ($q-1$) of LAA under different traffic loads (9 μs slots).

Percentile point	**λ (packets/second)**		
	0.5	**1.5**	**2.5**
100%	23	23	23
99%	22	22	21
95%	19	18	14
75%	8	10	10
50%	6	8	9
25%	3	6	7

percentile points. The proposed methods will thus adapt automatically to the new network conditions every time these change.

Dynamic CW with 3 adaptation points (DynCW-3)

Three adaptation points are defined in this method for the CW of LAA. These points are at the 50% (median value), 95% and 100% (maximum value) percentiles of the CDF of the existing Wi-Fi ON time periods. This method is implemented by setting the first upper bound of the LAA CW, $q-1$, to be the median (i.e., 50% value) Wi-Fi ON time. The reason behind choosing this value to be the starting point of the upper bound of the LAA CW is that in 50% of cases the Wi-Fi ON times will be shorter than this value and in the other 50% of cases they will be longer. Thus, the median value is considered a reasonable starting point. If the LAA transmission fails, this means that the 50% percentile time is not long enough to find a clear channel for LAA transmission and in such case the upper bound of the CW, $q-1$, will be increased to the 95% percentile point. In most cases, LAA should find an idle Wi-Fi channel after the new waiting time and therefore can transmit. For those cases where Wi-Fi has very long transmissions, the upper bound of the LAA CW will finally be updated to the 100% percentile point (maximum value), thus hopefully leading to a successful transmission in the next attempt. For this method, it can be noticed that the actual LAA waiting times are adapted based on the existing Wi-Fi traffic statistics.

Table 4.3: Upper bound CW values ($q-1$) of LAA using Cat 4 LBT, DynCW-3 and DynCW-2 methods under different traffic loads (9 μs slots).

λ (packets/second)	Cat 4 LBT	DynCW-3	DynCW-2
0.5	{15, 31, 63}	{6, 19, 23}	{6, 23}
1.5	{15, 31, 63}	{8, 18, 23}	{8, 23}
2.5	{15, 31, 63}	{9, 14, 23}	{9, 23}

Dynamic CW with 2 adaptation points (DynCW-2)

Two adaptation points are defined in this method for the CW of LAA. This method is implemented based on the Wi-Fi activity statistics as well. In particular, it defines the first maximum CW value at the 50% percentile (median value) point and finally at the 100% percentile (maximum value) point. The motivation of this method is to allow for a faster convergence to the optimum value of LAA CW, in case it needs to be increased, and therefore provide better performance for LAA by reducing latencies and increasing throughputs.

Illustrative examples of DynCW-3 and DynCW-2 methods

Table 4.3 depicts the maximum CW values using Cat 4 LBT, DynCW-3 and DynCW-2 methods under different traffic loads. For example, for $\lambda = 0.5$ packets/second, the maximum LAA CW values are {6, 19, 23} and {6, 23} for DynCW-3 and DynCW-2 methods, respectively, as observed from Table 4.2. On the other hand, the maximum LAA CW values for the standard 3GPP Cat 4 LBT algorithm are fixed regardless of the existing Wi-Fi activity statistics and they vary between {15, 31, 63}. It can be seen that the 3GPP Cat 4 LBT values of the upper bound LAA CW are significantly larger than those provided by the proposed methods for the different traffic loads. Thus, the 3GPP method may lead to unnecessarily long waiting times for LAA and therefore a degraded performance.

4.5.2 Static CW (StatCW) Method

A new static method is proposed here to select the upper bound of the LAA CW based on the activity statistics of the existing Wi-Fi network instead of updating the upper bound

Table 4.4: Upper bound CW values $(q-1)$ of LAA using StatCW method under different traffic loads (9 μs slots).

Percentile	λ **(packets/second)**		
point	**0.5**	**1.5**	**2.5**
100%	23	23	23
95%	19	18	14
50%	6	8	9

of the LAA CW dynamically [160]. In particular, the 50% (median value), 95% or 100% (maximum value) percentile point of the CDF of the ON Wi-Fi times are considered as fixed upper bounds of the LAA CW. In this proposed method, $q-1$ is considered to be a static value that is selected as the corresponding value for the percentile point of the CDF of the ON Wi-Fi times divided by the CCA slot duration (9 μs). Table 4.4 shows corresponding values of the LAA CW, $q-1$, for these percentile points of the CDF of the ON Wi-Fi times under different traffic loads. Therefore, the upper bound of the LAA CW is fixed and there are no different sizes for the CW size as specified in the 3GPP Cat 4 LBT algorithm where the upper bound of the CW could be 15, 31 or 63. The main motivation of this method is to allow a faster convergence to the prospective optimum LAA CW, thus further reducing LAA waiting times that should lead to lower latency and higher throughput for LAA.

4.5.3 Fixed Waiting Time (FWT) Method

In the 3GPP Cat 4 LBT algorithm, the channel is observed by the LAA eNB for a time equal to N multiplied by the CCA slot time period (e.g., 9 μs) where N is a uniform random number within the interval $N \in [0, q-1]$ and $q-1$ is the upper bound of the LAA CW, which is updated based on HARQ feedbacks to 15, 31 and 63. It can be noted that the number of idle slots that need to be observed by the eNB is random and constrained by the upper bound of the LAA CW. The random choice for the number of idle slots that need to be observed by the LAA eNB before transmission may not be the most appropriate approach since such random choice is somehow arbitrary and independent of the actual Wi-Fi activity statistics. This suggests that a fixed waiting time, if properly configured based on the Wi-Fi activity statistics, may lead to a more efficient operation, which motivates the idea considered in this subsection. This knowledge of the existing Wi-Fi network activity statistics can be exploited to allow the LAA eNB to wait a fixed (rather than random) amount of slots before attempting a new transmission. Setting a fixed waiting time, if properly configured, should allow a faster convergence to the optimum operating point than dynamic approaches. Therefore, in order to enhance the 3GPP Cat 4 LBT algorithm, a new method with a fixed waiting time before transmission for LAA is proposed based on the activity statistics of the existing Wi-Fi network. The dashed shaded boxes in Fig. 4.1 highlight the procedure of the 3GPP Cat 4 LBT algorithm that need to be modified to implement the proposed Fixed Waiting Time (FWT) method for LAA.

Notice that three key changes to the 3GPP standard approach are considered in this method. Firstly, there is no backoff process, which to some extent reduces the complexity of the algorithm since random number generators are not required in this case. Secondly, there is no adaptation of the LAA CW based on the received HARQ reports (in fact, there is no CW in this case), which also contributes to simplify the algorithm and reduce its complexity. Thirdly, the knowledge of the activity statistics of the existing Wi-Fi network is required to set a fixed waiting time before transmission for the LAA eNB. The LAA eNB waiting time is set as N multiplied by the CCA slot time (9 μs) where N can be set based on the percentile point of the CDF for the ON time periods of the existing Wi-Fi network divided by the CCA slot time (9 μs) as shown in Table 4.4.

4.5.4 Variants of the Proposed Waiting Time Adaptation Methods

The previous proposed dynamic and static CW methods, including the standard 3GPP Cat 4 LBT algorithm, consider various implementations to adapt/select the upper bound of the LAA CW. All these methods propose different approaches to tune the upper bound of the LAA CW but they have not proposed any strategy to adapt/select the lower bound of the LAA CW. Exploiting the knowledge of the activity statistics of the existing Wi-Fi network to select the lower bound of the LAA CW may provide a more efficient channel access mechanism for LAA. Various methods are proposed here to select the lower bound of the CW of LAA based on the activity statistics of the existing Wi-Fi network. The ideas suggested in this section to select the lower bound of the CW can also be applied to the FWT method, thus leading to new variants of this method as well.

Variants based on shortest (minimum) Wi-Fi ON time

It can be noted that the lower bound of the LAA CW in the methods discussed so far (including the Cat 4 LBT and proposed CW-based methods) is set to zero regardless of the HARQ feedbacks or even of the activity statistics of the existing Wi-Fi network. This value means that the LAA eNB may start the backoff process by selecting a random number $N \in [0, q-1]$, which could be zero or any small value within the interval $[0, q-1]$. This selection process may not be efficient for LAA transmission since this small value of N may not be long enough to find a clear channel given that it may lead to shorter waiting times than the actual occupancy times of the Wi-Fi transmissions, and as a result LAA would attempt to access a channel which is not free, thus leading to a backoff process repetition and therefore degrading the performance of the coexisting networks. Consequently, new variants of the methods discussed so far are here proposed by selecting the lower bound of the LAA CW based on the minimum ON activity time of the existing Wi-Fi network. Thus, the LAA eNB starts the backoff process by selecting a random number $N \in [N_{Min}, q-1]$, where N indicates the number of idle slots that need to be observed before transmission, N_{Min} is the lower bound of the CW and $q-1$ represents the upper bound of the CW. The value of N_{Min} is obtained as the minimum ON activity time of the Wi-Fi Network divided by the LAA slot duration (e.g., 9 μs) and rounding the result to the nearest integer toward infinity (i.e., ceil function), while the upper bound of the CW, $q-1$, is selected as discussed for each proposed method in Sections 4.5.1 and 4.5.2.

The motivation of these variants is that selecting any random number by the LAA eNB below N_{Min} may not be a wise decision since the channel will likely still be busy (i.e., in use by a Wi-Fi transmission) within that time period. Therefore, to minimise the number of unfruitful backoffs, the minimum waiting time of the considered methods is adapted according to the minimum Wi-Fi ON activity time.

Variants based on most frequent (mode) Wi-Fi ON time

The variants proposed in this section select the lower bound of the LAA CW based on the most frequent occurring ON time of the existing Wi-Fi network (i.e., the mode of the ON times). In particular, the LAA eNB starts the backoff process by selecting a random number $N \in [N_{Mode}, q-1]$ where N indicates the number of idle slots that need to be observed before transmission, N_{Mode} is the lower bound of the CW and $q-1$ represents the upper bound of the CW. The value of N_{Mode} is obtained as the mode of the ON activity time of the Wi-Fi network divided by the LAA slot duration (e.g., 9 μs) and rounding the result to the nearest integer toward infinity (i.e., ceil function), while the upper bound of the CW, $q - 1$, is selected as discussed for each proposed method in Sections 4.5.1 and 4.5.2. The motivation for this variant is that adjusting the LTE-LAA minimum waiting times based on the most frequent Wi-Fi ON time might potentially lead to a more efficient coexistence between LTE-LAA and Wi-Fi networks in the same unlicensed channel, and this motivates the consideration of this variant in this chapter.

Fig. 4.3 summarises the complete set of methods that can be used to adapt the LTE-LAA waiting times, including both the 3GPP Cat 4 LBT method and the methods proposed in this chapter, along with the possible variants.

4.6 Method to Adapt LTE Transmission Times

Spectrum regulators impose constraints on the maximum transmission duration for any wireless communications system operating over unlicensed channels. As a result, a predefined transmission period (TxOP) for LAA eNB is mandatory for transmissions over unlicensed bands. This transmission period determines for how long an LTE-LAA transmission may last, after which the transmission must finish (even if there are more data to transmit) in order to allow other users to access the unlicensed channel. The standard 3GPP Cat 4 LBT algorithm implements a configurable but fixed TxOP parameter that depends on the channel access priority class (see Table 4.1 and [162, Table 15.1.1-1] for details). This duration of TxOP, once selected, will remain constant during the LAA eNB operation.

This static scheme for the transmission of LAA over unlicensed bands may be unsuitable since a fixed TxOP may not lead to an efficient spectrum utilisation. In particular, the unlicensed channel may suffer from different traffic conditions and a dynamic TxOP scheme would be more efficient for spectrum utilisation, thus leading to better performance for the coexisting networks. In specific, when the Wi-Fi traffic load is low, the channel can be expected to be idle for longer time periods and these periods can be exploited for LAA transmissions for longer intervals, thus providing better performance (i.e., using longer TxOP period). On the other hand, a shorter TxOP period for LAA would be more suitable when the Wi-Fi traffic load is high since the use of a long TxOP period in such cases would lead to more collisions in the channel and degrade the performance for the coexisting networks. As a result, the static TxOP period scheme may not be the most suitable

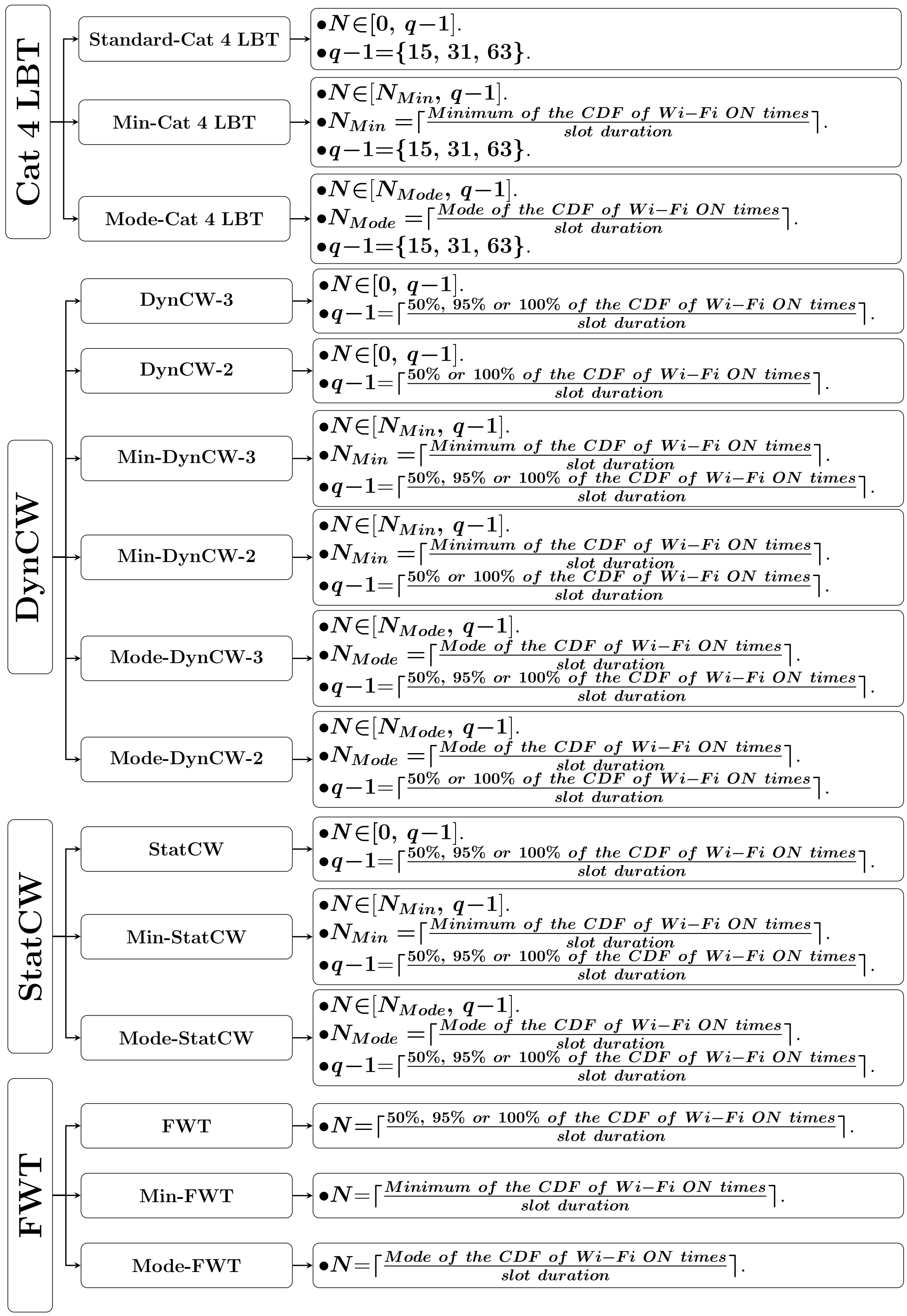


Figure 4.3: Proposed methods to adapt LTE waiting times and their variants.

scheme for an efficient coexistence between LTE-LAA and Wi-Fi networks over unlicensed spectrum bands. Thus, a novel scheme is proposed here to adapt the TxOP period for LAA dynamically in order to improve the performance of the coexisting networks. The dashed shaded diamond in Fig. 4.1 highlights the procedure of the 3GPP Cat 4 LBT algorithm that will be modified to implement the proposed dynamic TxOP method for LAA.

The new proposed method selects the TxOP for LAA based on the current size of the CW for LAA, which is a parameter readily available in any practical implementation of LAA [161]. The 3GPP Cat 4 LBT algorithm adapts the size of the CW for LAA based on the HARQ feedbacks, which reflect incorrect data transmission due to a congestion or a collision in the channel. Therefore, the current CW size can be seen as an indication of the current level of congestion in the unlicensed channel and used to adapt the TxOP accordingly. The proposed method considers two adaptation points for the maximum TxOP period of LAA as shown in Table 4.5, where the TxOP can dynamically range from 4 ms to 20 ms. This range of values for the TxOP has been selected to illustrate the full potential benefits of the method proposed in this section, but can be adjusted, where required, to specific local spectrum regulations, or optimised for specific ranges of traffic loads. According to the adaptation points shown in Table 4.5, when the LAA CW size is 15 (i.e., the minimum LAA CW size), the TxOP parameter is set to its maximum value of 20 ms. Otherwise, the TxOP period parameter is set to 4 ms, which is the minimum TxOP period considered. The reason behind choosing the maximum TxOP period (20 ms) for the lower value of the CW size is that the lower CW size is associated with low volume of Wi-Fi traffic, therefore a longer LAA transmission should be reasonable in this case since this low volume of Wi-Fi traffic means more idle times in the channel, which can be exploited for LAA transmissions by setting TxOP period to its maximum value, thus improving the LAA performance without degrading the Wi-Fi performance. On the other hand, the LAA CW size is increased to 31 or 63 in the 3GPP Cat 4 LBT algorithm due to the channel congestion or transmission collisions, therefore the TxOP period is set here to its minimum value (4 ms) in order to reduce this congestion/collision, thus providing better performance for LAA and not degrading the performance of the existing network (i.e., Wi-Fi).

It is worth mentioning that the proposed dynamic approach for the TxOP period of LAA is based on the traffic statistics of the coexisting networks through the received HARQ feedbacks. Thus, the key change between the 3GPP standard and the proposed approach is the use of a dynamic TxOP period instead of a static one. This dynamic

Table 4.5: Value of the selected TxOP period as a function of the LAA CW size for the dynamic TxOP method.

CW Size	**TxOP Period**
15	20 ms
31	4 ms
63	4 ms

adaptation for the TxOP of LAA can achieve better alignment between Wi-Fi idle times and LTE-LAA transmission times, thus reducing the number of collisions and achieving a better performance for the coexisting networks compared with the 3GPP Cat 4 LBT algorithm, which considers a fixed TxOP period for LTE-LAA transmissions regardless of the congestion/collision over the unlicensed channel. In addition, the proposed approach can be easily implemented in a real system without adding any significant modifications to current commercial products since the approach is mainly based on the LAA CW parameter which is a readily available in any practical implementation of LAA.

4.7 Simulation Methodology and Setup

The indoor scenario defined in [96] is considered in this chapter to verify the effectiveness of the proposed methods in providing a fair coexistence between LTE-LAA and Wi-Fi networks over unlicensed bands in terms of throughput and latency. In particular, the proposed methods are evaluated based on the 3GPP definition of fairness, where the LAA network should not impact the Wi-Fi network performance more than an additional Wi-Fi network operating on the same carrier in terms of throughput and latency.

In order to estimate the activity statistics of the existing Wi-Fi network, two Wi-Fi networks are deployed together over the same unlicensed band. The CDF of the ON times of the existing Wi-Fi network can be estimated for this scenario and exploited to adapt/select the CW boundaries, the transmission waiting times and the transmission opportunity time for LAA. In particular, various statistical values can be evaluated from this CDF such as the percentile point at the 50%, 95% and 100% of the CDF. In addition, the minimum and mode can be evaluated from the CDF as well. These various statistical values are used in the implementations of the different proposed methods. Afterwards, one of these deployed Wi-Fi networks is replaced with an LTE-LAA network allowing an

LTE-LAA/Wi-Fi coexistence scenario and assessing the validity of the various proposed methods. The LTE-LAA/Wi-Fi coexistence scenario is compared with the Wi-Fi/Wi-Fi scenario in order to determine how the introduction of an LTE-LAA network operating with the proposed methods affects and existing Wi-Fi network with respect to the introduction of an additional Wi-Fi network, therefore providing an accurate assessment of the coexistence fairness as defined by the 3GPP.

The methodology for evaluating the coexistence performance of LTE-LAA and Wi-Fi follows the 3GPP TR 36.889 simulation conditions except the updating rule of the LAA CW, where the proposed CW methods are implemented. In addition, a dynamic TxOP approach is implemented instead of the static TxOP approach of the 3GPP to assess the validity of the proposed dynamic TxOP method. In this study, all methods are evaluated using the event driven simulator ns-3 with LAA extension [129]. This simulator is an open source simulator and it allows researchers to share their contributions [95, 96]. In this simulator, WifiNetDevice can coexist with other NetDevices and an LTE module was implemented and developed by the LENA project to evaluate the performance of issues in LTE systems such as radio resource management algorithms, cognitive LTE systems and DL/UL MAC schedulers [131].

In this chapter, an indoor scenario in a single floor building is adopted as specified by 3GPP by considering two operators; operator A (Wi-Fi) and operator B (LAA) using the same 20 MHz channel over the unlicensed 5 GHz band [96]. The LAA/Wi-Fi indoor scenario is shown in Fig. 2.2. Operator A (Wi-Fi) deploys four APs while operator B (LAA) deploys four eNBs. All the base stations (i.e., APs and eNBs) are equally spaced and centred along the shorter dimension of the building. Moreover, each operator deploys 20 stations (STAs)/User Equipments (UEs) randomly distributed in a one floor building with a rectangular area. All base stations (i.e., APs and eNBs) and users (i.e., STAs and UEs) are equipped with two antennas for 2x2 MIMO operation. The traffic is modelled as a File Transfer Protocol (FTP) Model 1 operating over User Datagram Protocol (UDP) considering DL scenario. This model simulates file transfers according to a Poisson process with an arrival rate of λ packets/second. The file size considered is 0.5 MB with different recommended arrival rates ($\lambda = 0.5, 1.5, 2.5$ packets/second), which are simulated to generate different load levels with simulation duration of 240 seconds [96]. Notice that the packet size of 0.5 MB is the size of the Protocol Data Unit (PDU) at the application layer. The ns-3 simulator implements the whole set of layers of the protocol stack and these packets are split into smaller pieces of data for transmission according to the PDU size at each level of the protocol stack. The details of the employed simulation parameters are shown in Table 4.6 along with the 3GPP reference scenario.

The coexisting Radio Access Technologies (RATs) detect each other based on an Energy Detection (ED) principle. Wi-Fi nodes can detect other Wi-Fi nodes at –82 dBm and LAA nodes at –62 dBm. On the other hand, LAA nodes can detect Wi-Fi nodes at –72 dBm. This means that Wi-Fi will defer to weaker Wi-Fi signals sensed on the channel compared to LTE signals, which are detected at –62 dBm. It is worth noting that the selected decision thresholds can have a significant impact on the performance of both coexisting networks in some scenarios. As extensively investigated and shown in [167], a careful selection of the thresholds can lead to an improved performance. This aspect, however, is out of the scope of this work and thus the default values presented above, which are defined in [96], are here considered. The parameter that describes the maximum length of transmission for LAA (i.e., the TxOP) is configurable and is set to be 8 ms in the Cat 4 method, CW methods and FWT methods. On the other hand, the TxOP parameter is configured dynamically within the dynamic TxOP method. The CW size is adapted as defined in Section **??** for the 3GPP Cat 4 LBT method and in Section 4.5 for the proposed CW selection methods.

The performance of the considered LTE-LAA/Wi-Fi coexistence methods is evaluated based on the main performance metrics described in 3GPP TR 36.889 (i.e., throughput and latency). Throughput is measured as the amount of data correctly transmitted within a specified time period as observed at the IP layer, while latency is measured as the time elapsed since the packet leaves the transmitter until it reaches the receiver.

4.8 Simulation Results

In this section, the performance of LTE-LAA and Wi-Fi networks is analysed using the proposed methods. The results are shown in terms of the individual throughputs and latencies for each network as well as the total aggregated throughput for both networks. To validate the performance of the proposed methods, the fairness definition as specified by 3GPP is considered based on the throughput and latency for 95% of the users. The results at various percentiles (90%, 95% and 100%) were evaluated in the context of this work and it was observed that the main trends and conclusions are similar in all cases. However, only the results for the 95% percentile case are provided here for the sake of brevity.

Table 4.6: Simulation parameters (see [96, Annex A.1.1] for details).

	3GPP TR 36.889	**ns-3 simulator**
Network layout	Indoor scenario	Indoor scenario
System bandwidth	20 MHz	20 MHz
Carrier frequency	5 GHz	5 GHz (Ch.36)
Max. total BS Tx power	18/24 dBm	18 dBm
Max. total UE Tx power	18 dBm	18 dBm
Pathloss, shadowing & fading	ITU Indoor/Hotspot	IEEE 802.11n
Antenna pattern	2D omni-D	2D omni-D
Antenna height	6 m	6 m for LAA
UE antenna height	1.5 m	1.5 m for LAA
Antenna gain	5 dBi	5 dBi
UE antenna gain	0 dBi	0 dBi
UE dropping	Randomly	Randomly
Traffic model	FTP model 1 & 3	FTP model 1

4.8.1 Dynamic CW (DynCW) Methods

The coexistence of LTE-LAA and Wi-Fi networks is analysed here when LTE-LAA implements the proposed dynamic CW methods. The throughputs for the existing Wi-Fi network (i.e., operator A) under different traffic loads (i.e., different arrival rates) for various methods are presented in Fig. 4.4. The reference case represents a homogeneous scenario where the existing Wi-Fi network (operator A) coexists with another Wi-Fi network (operator B), while the other cases correspond to heterogeneous coexistence scenarios (i.e., Wi-Fi and LAA) where operator A is a Wi-Fi network and operator B is an LTE-LAA network. Based on the 3GPP fairness definition, an ideal LAA coexistence mechanism should allow the Wi-Fi network achieve at least the same performance as in the reference case without (ideally) experiencing any performance degradation. It can be seen that operating LAA using the Cat 4 LBT algorithm leads to a lower throughput performance for the Wi-Fi network than in the reference case for all traffic loads, which contradicts the 3GPP fairness definition. Compared to the 3GPP Cat 4 LBT method, the proposed dynamic CW methods (in particular the DynCW-2 method) achieve a comparable Wi-Fi

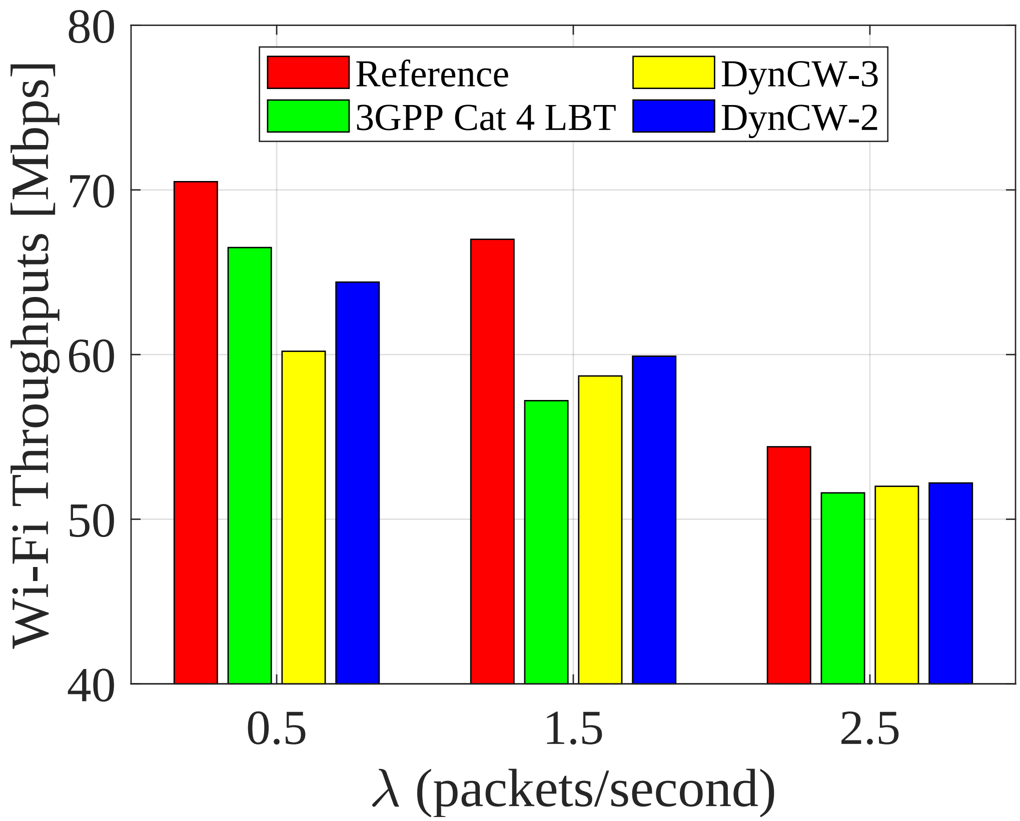


Figure 4.4: Wi-Fi throughput performance of the proposed dynamic CW methods.

throughput performance under low traffic loads (λ = 0.5 packets/second) and a slightly better performance under higher traffic loads (λ = 1.5 and 2.5 packets/second). Even though it can be seen from Fig. 4.4 that the fairness definition in terms of Wi-Fi throughput is not fully met with the proposed dynamic CW methods (DynCW-3 and DynCW-2 methods) for the different traffic loads, the proposed dynamic CW methods degrade the throughput performance of the existing Wi-Fi network to a lesser extent and therefore can be considered to be more friendly to Wi-Fi networks than the 3GPP Cat 4 LBT method. It is worth noting that the DynCW-2 method in general outperforms DynCW-3; this suggests that the two-point adaptation process of the CW performed by DynCW-2 allows a faster convergence to an appropriate CW size when this is required by the Wi-Fi traffic conditions.

Fig. 4.5 shows the Wi-Fi latency performance under different traffic loads for the

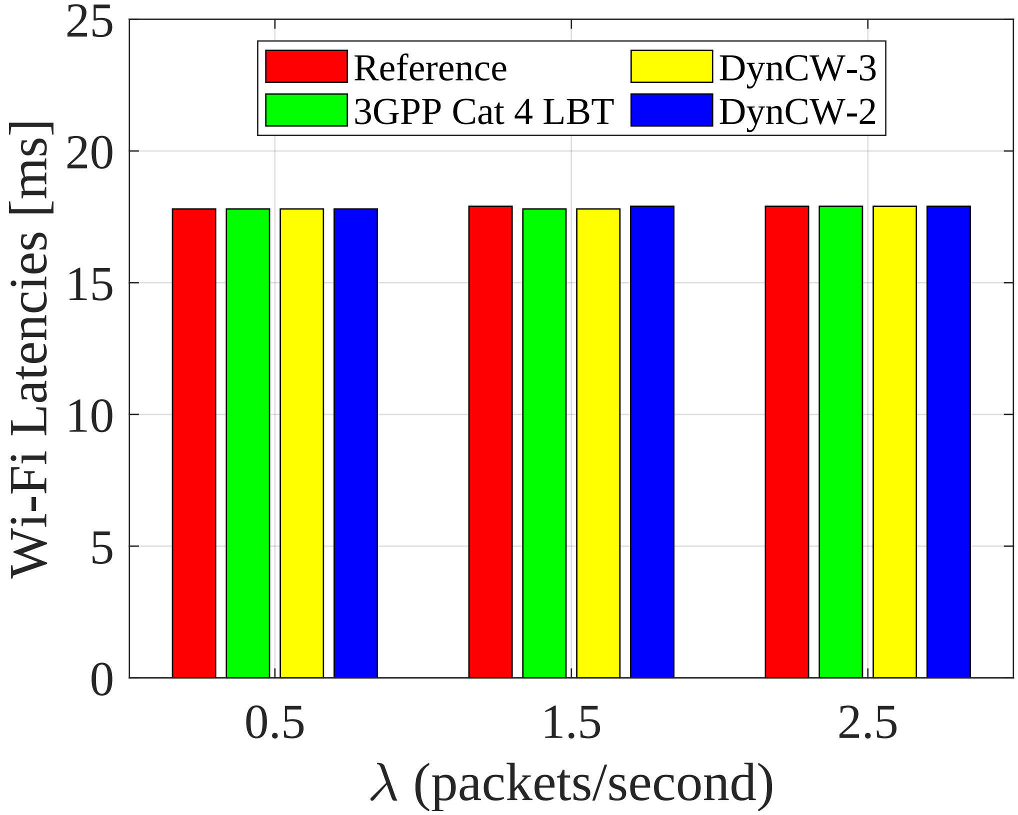


Figure 4.5: Wi-Fi latency performance of the proposed dynamic CW methods.

various methods. It can be noted that all methods lead to a similar latency performance as the reference case, which means that the latency experienced by the existing Wi-Fi network is not significantly affected by the presence of other (Wi-Fi or LTE-LAA) networks.

The LAA throughput performance is illustrated in Fig. 4.6. It can be noticed that the proposed methods achieve better LAA throughputs compared to the standard Cat 4 LBT method as the traffic load increases. The LAA throughputs are improved using the proposed methods due to the smart selection of the upper bound of the LAA CW based on the Wi-Fi activity statistics. This approach in the proposed dynamic CW methods allows the LAA eNB to access the channel faster than the Cat 4 LBT method, thus removing unnecessary waiting times for the LTE-LAA network and providing better LAA throughputs. As high traffic demands are expected in the future, high performance at high values of λ is therefore more desirable.

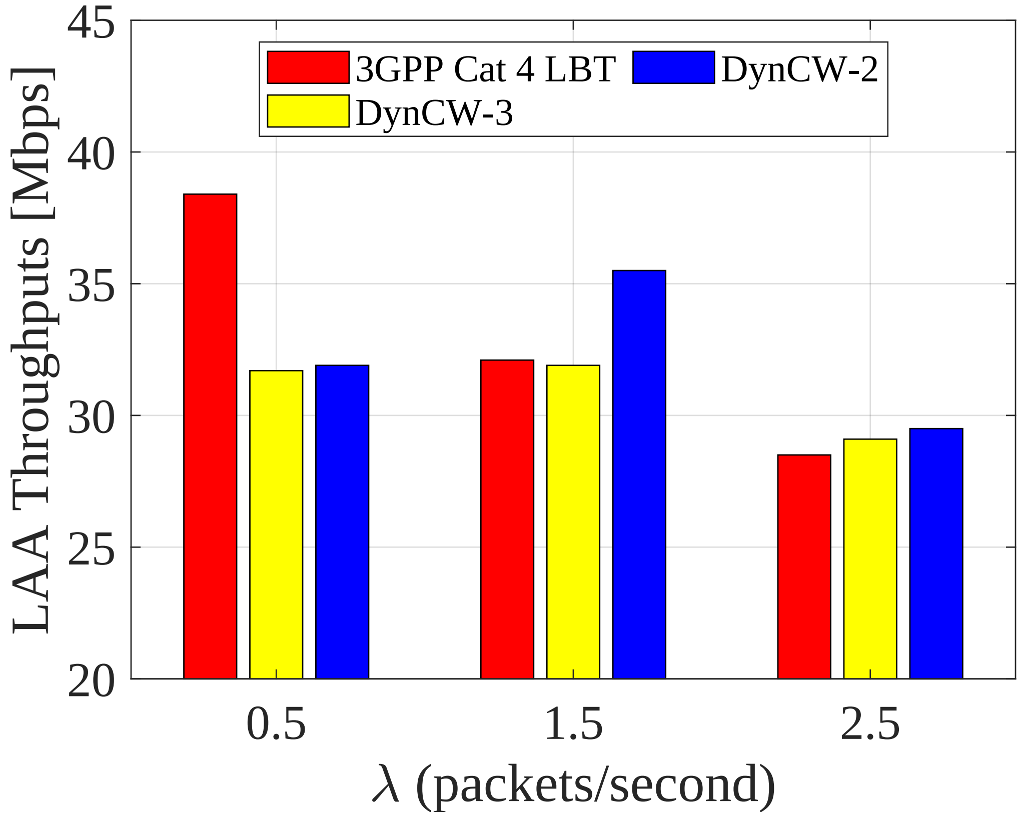


Figure 4.6: LTE-LAA throughput performance of the proposed dynamic CW methods.

Finally, the total aggregated throughputs for both coexisting networks (i.e., Wi-Fi and LAA) are shown in Fig. 4.7. It can be seen that the proposed dynamic CW methods achieve better total aggregated throughputs compared to Cat 4 LBT at higher traffic loads. Specifically, the performance improvement in the total aggregated throughputs using the DynCW-3 method compared to the Cat 4 LBT method is 1.5% (1.3 Mbps) and 1.2% (1 Mbps) for $\lambda = 1.5$ and 2.5 packets/second, respectively. Moreover, the performance improvement in the total aggregated throughputs using the DynCW-2 method compared to the Cat 4 LBT method is 6.8% (6.1 Mbps) and 2% (1.6 Mbps) for $\lambda = 1.5$ and 2.5 packets/second, respectively. Overall, it can be noticed that the proposed dynamic CW methods can achieve a slightly better performance (for both Wi-Fi and LTE-LAA networks) compared to the standard Cat 4 LBT method under high traffic loads and therefore constitute more convenient coexistence approaches in such scenario (in particular the DynCW-2

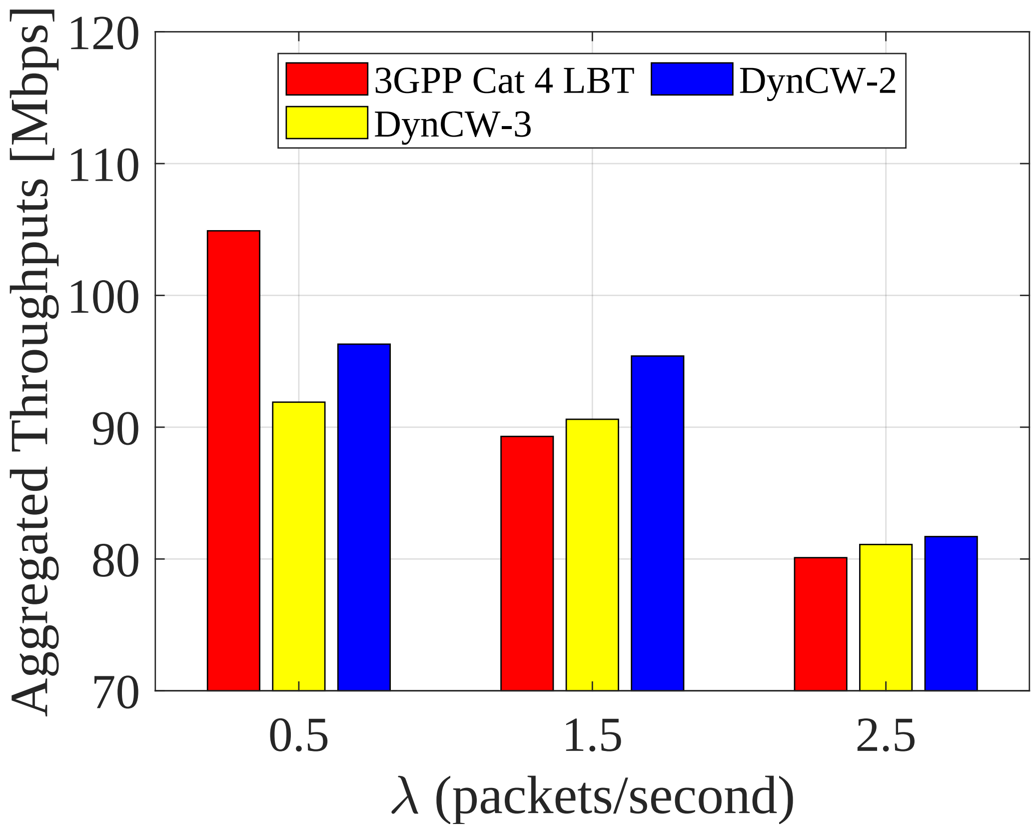


Figure 4.7: Aggregated throughput performance of the proposed dynamic CW methods.

method).

4.8.2 Static CW (StatCW) Method

The performance of LTE-LAA and Wi-Fi networks is analysed here using the proposed static CW method. The throughputs for the coexisting networks (i.e., Wi-Fi and LAA) for the different percentile points at 50%, 95% and 100% of the CDF of the ON times of the existing Wi-Fi network using the proposed static CW method are provided in Table 4.7. It can be seen that for the different traffic loads (i.e., different arrival rates) the 100% percentile point (maximum value) achieves the best performance in terms of Wi-Fi throughput with a rather constant performance in terms of LAA throughput. Table 4.8 provides the Wi-Fi latencies at the different percentile points of the CDF using the

Table 4.7: Wi-Fi/LAA throughput performance [Mbps] for 95% of users using the StatCW method at different percentile points of the CDF of Wi-Fi ON times.

Percentile	**λ (packets/second)**		
point	**0.5**	**1.5**	**2.5**
100%	80.9/31.1	62.4/33.9	53.5/27.9
95%	74.1/31.8	60.0/32.3	52.5/28.2
50%	59.9/30.6	57.7/29.5	51.9/28.1

Table 4.8: Wi-Fi latency performance [ms] for 95% of users using the StatCW method at different percentile points of the CDF of Wi-Fi ON times

Percentile	**λ (packets/second)**		
point	**0.5**	**1.5**	**2.5**
100%	17.9	17.8	17.9
95%	17.9	17.9	17.9
50%	17.9	17.8	17.9

proposed static CW method. It can be seen that all percentile points (i.e., 50%, 95% and 100%) provide comparable performances in terms of Wi-Fi latency. Thus, the 100% percentile point of the ON Wi-Fi times will be considered to select the upper bound of the LAA CW in the proposed static CW method since this choice leads to the best Wi-Fi performance (LTE-LAA performance is unaffected by the selected percentile point).

The Wi-Fi throughput performance of the proposed static CW method is presented and compared to the reference and 3GPP Cat 4 LBT cases in Fig. 4.8. It can be observed that the proposed static CW method achieves better throughput for the existing Wi-Fi network (i.e., operator A) for all traffic loads compared to the standard Cat 4 LBT method. In addition, it provides better throughput for the existing Wi-Fi network compared to the reference case at lower traffic loads ($\lambda = 0.5$ packets/second) and comparable throughput performance at medium and higher traffic loads ($\lambda = 1.5$ and 2.5 packets/second). Even though the fairness requirement in terms of throughput is not fully met for all traffic loads (concretely, for $\lambda = 1.5$ packets/second), the proposed static CW method provides a very close approximation, with a noticeably better performance than the standard Cat 4 LBT method. Comparing the results shown in Figs. 4.4 and 4.8, it can be noted that the static

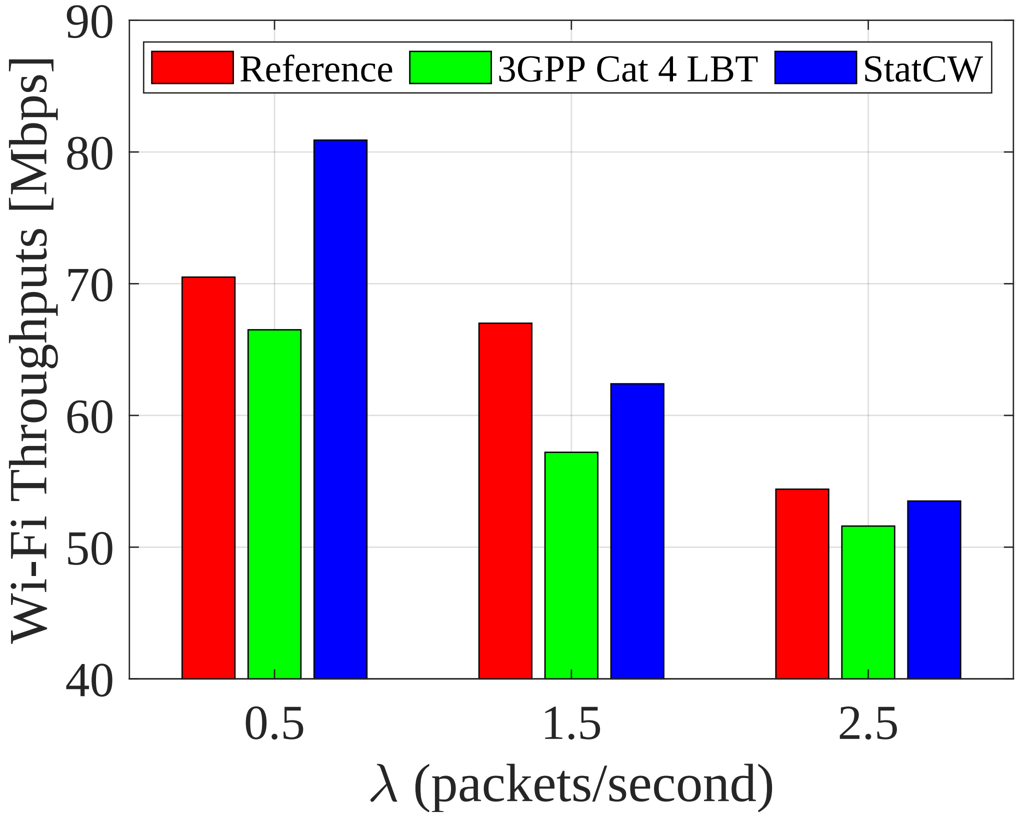


Figure 4.8: Wi-Fi throughput performance of the proposed static CW method.

CW method provides in general a better Wi-Fi throughput performance than the dynamic CW method as well.

The latencies of the existing Wi-Fi network are presented in Fig. 4.9 for the reference, Cat 4 LBT and static CW methods under different traffic loads. Comparable latencies for all traffic loads can be seen compared to the reference case. As a result, both Cat 4 LBT and static CW methods do not degrade the existing Wi-Fi performance in terms of latency.

The throughputs for LAA (i.e., operator B) using the Cat 4 LBT and static CW methods under different traffic loads are presented in Fig. 4.10. Comparing this figure with the results shown in Fig. 4.6 for the dynamic CW methods, it can be noted that the LAA throughput performance is quite comparable in both cases, with the LAA throughput for the static CW method being slightly lower than that attained by the best dynamic

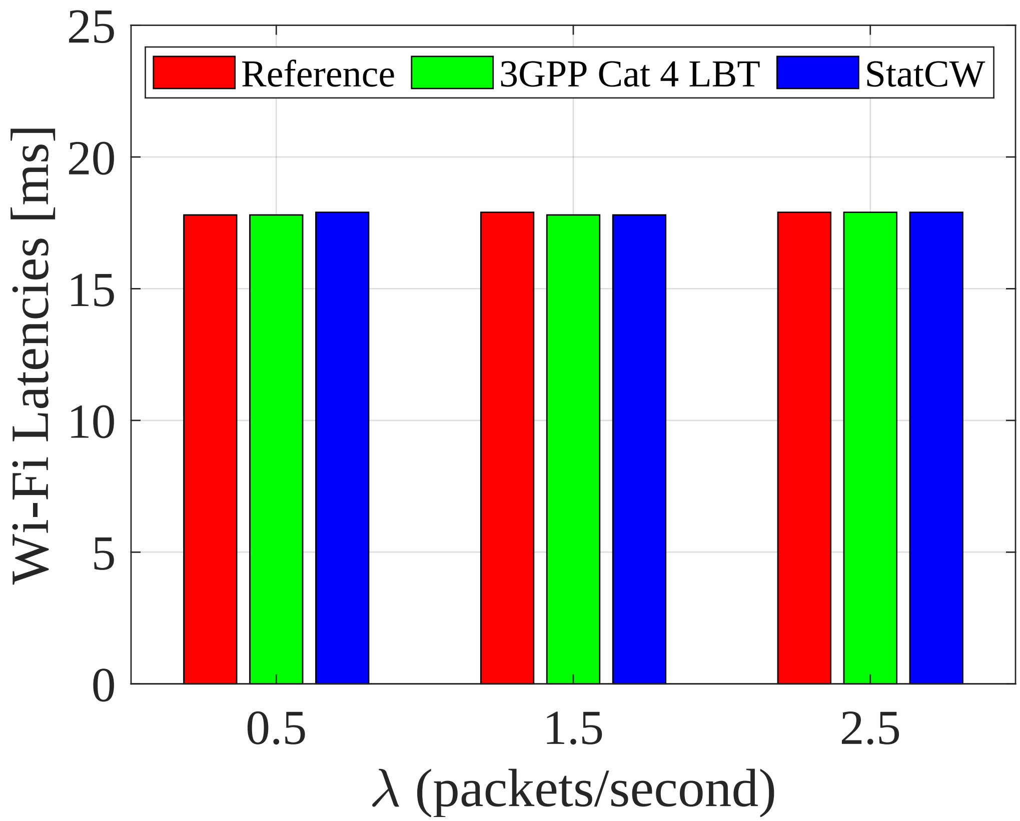


Figure 4.9: Wi-Fi latency performance of the proposed static CW method.

CW method. This slight reduction of the LAA throughput with the static CW method compared to the dynamic CW method is the price to be paid in order to achieve a better Wi-Fi throughput performance that, as shown in Fig. 4.8 for the static CW method, meets more closely the 3GPP definition of fairness. The existence of a tradeoff between the Wi-Fi and LAA throughput performances seems reasonable. However, it is interesting to note that the slightly degraded LAA throughput of the static CW method with respect to the dynamic CW method leads to a comparatively larger improvement of the Wi-Fi throughput. This can be clearly seen by comparing the total aggregated throughput of the static CW method (shown in Fig. 4.11) with the total aggregated throughput of the dynamic CW methods (shown in Fig. 4.7). The static CW method outperforms the 3GPP Cat 4 LBT method in terms of aggregated throughput for all traffic loads (including $\lambda = 0.5$ packets/second, where the performance of the best dynamic CW method was still lower

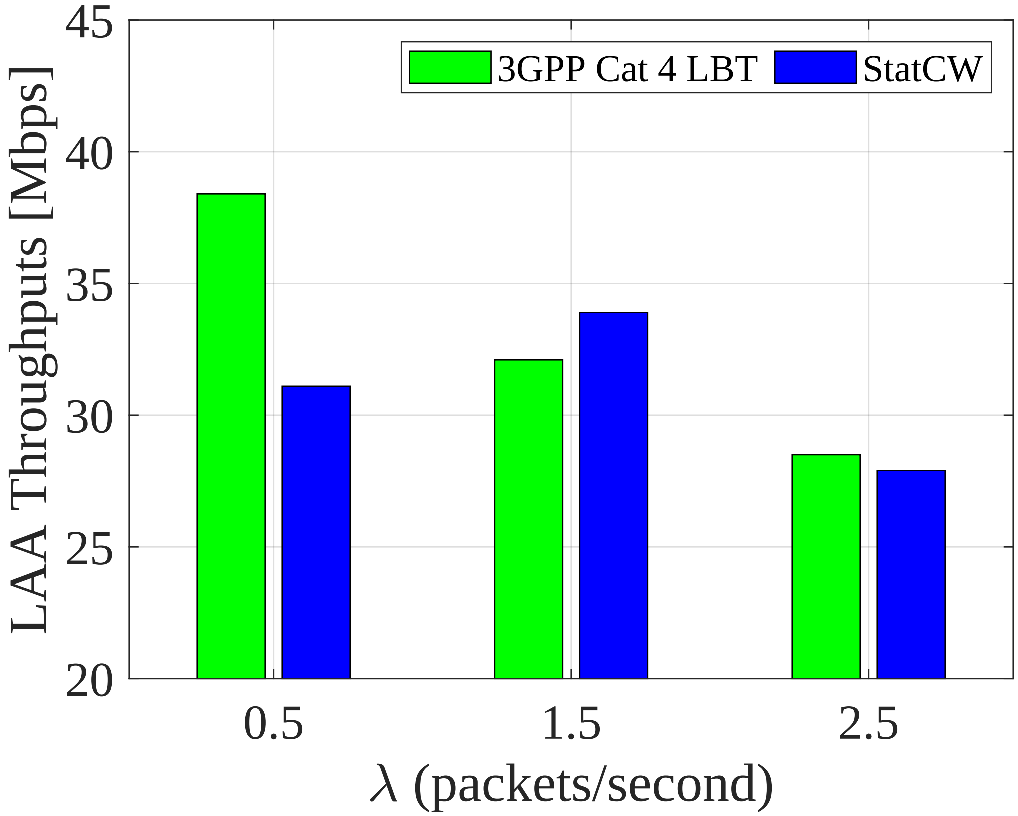


Figure 4.10: LTE-LAA throughput performance of the proposed static CW method.

than that of the 3GPP Cat 4 LBT). Moreover, the performance improvements of the static CW method with respect to the Cat 4 LBT method are greater than those achieved by the best dynamic CW method, concretely 6.8% (7.1 Mbps), 7.8% (7 Mbps) and 1.6% (1.3 Mbps) for $\lambda = 0.5$, 1.5 and 2.5 packets/second, respectively.

Based on the obtained results, it can be concluded that the static CW method not only is more convenient than the 3GPP Cat 4 LBT method but also than the best dynamic CW method in terms of fairness. In general, the static CW method allows the Wi-Fi network experience a higher throughput performance that is closer to the scenario of fair coexistence as defined by the 3GPP. On the other hand, the LTE-LAA performance remains quite stable and, as a result, the overall aggregated performance of both networks is significantly higher with the static CW method.

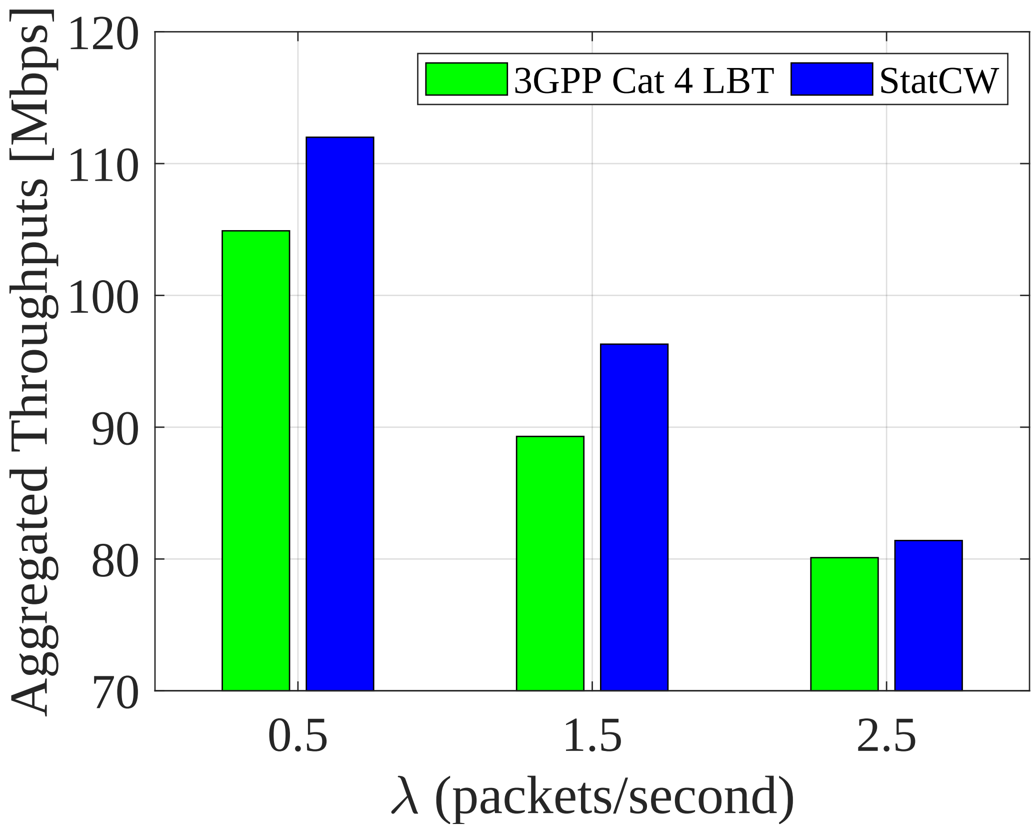


Figure 4.11: Aggregated throughput performance of the proposed static CW method.

4.8.3 Fixed Waiting Time (FWT) Method

The performance of LTE-LAA and Wi-Fi networks is investigated here using the proposed FWT method for LAA. Fig. 4.12 depicts the throughputs for the existing Wi-Fi network under different traffic loads for the reference, Cat 4 LBT and fixed waiting times methods. It can be seen that the proposed FWT method provides better throughput for the existing Wi-Fi network for all traffic loads compared not only to the standard Cat 4 LBT method but also to the reference case. This means that the existing Wi-Fi network (operator A) experiences a better throughput performance when the coexisting network (operator B) is an LTE-LAA network using the proposed FWT method than when it is another Wi-Fi network. This means that the proposed FWT method not only meets the 3GPP fairness requirement in terms of throughput but in fact leads to an improved throughput

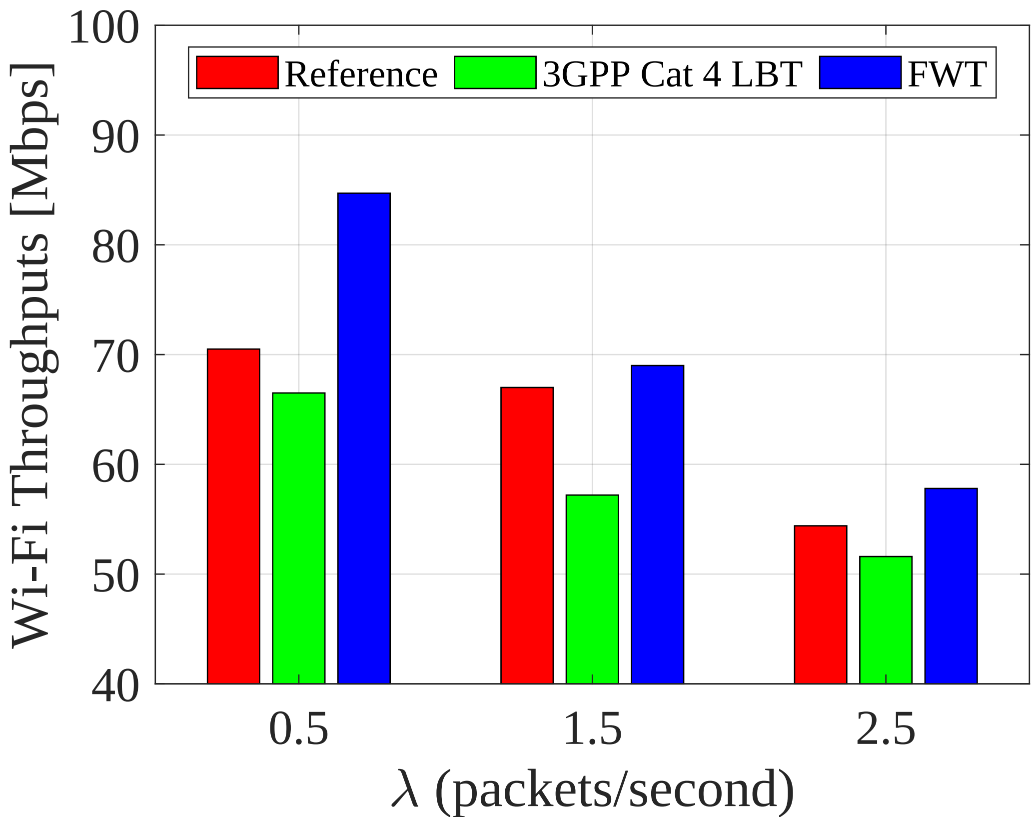


Figure 4.12: Wi-Fi throughput performance of the proposed FWT method.

performance for the existing Wi-Fi network when an LTE-LAA network is introduced (compared to the introduction of another Wi-Fi network). This may be explained by the ability of the proposed FWT method to select a suitable amount of waiting time before attempting a transmission such that there is a high chance to find a free channel without waiting unnecessarily long times, which can in turn be ascribed to the selection of such waiting time based on the Wi-Fi activity statistics.

Fig. 4.13 presents the latencies of the existing Wi-Fi network for the reference, Cat 4 LBT and FWT methods under different traffic loads. It can be seen that all methods provide comparable latencies for all traffic loads. As a result, both Cat 4 LBT and FWT methods do not degrade the performance of the existing Wi-Fi network in terms of latency.

Fig. 4.14 depicts the throughputs for LAA (i.e., operator B) using the Cat 4 LBT and FWT methods under different traffic loads. It can be seen that the significant throughput

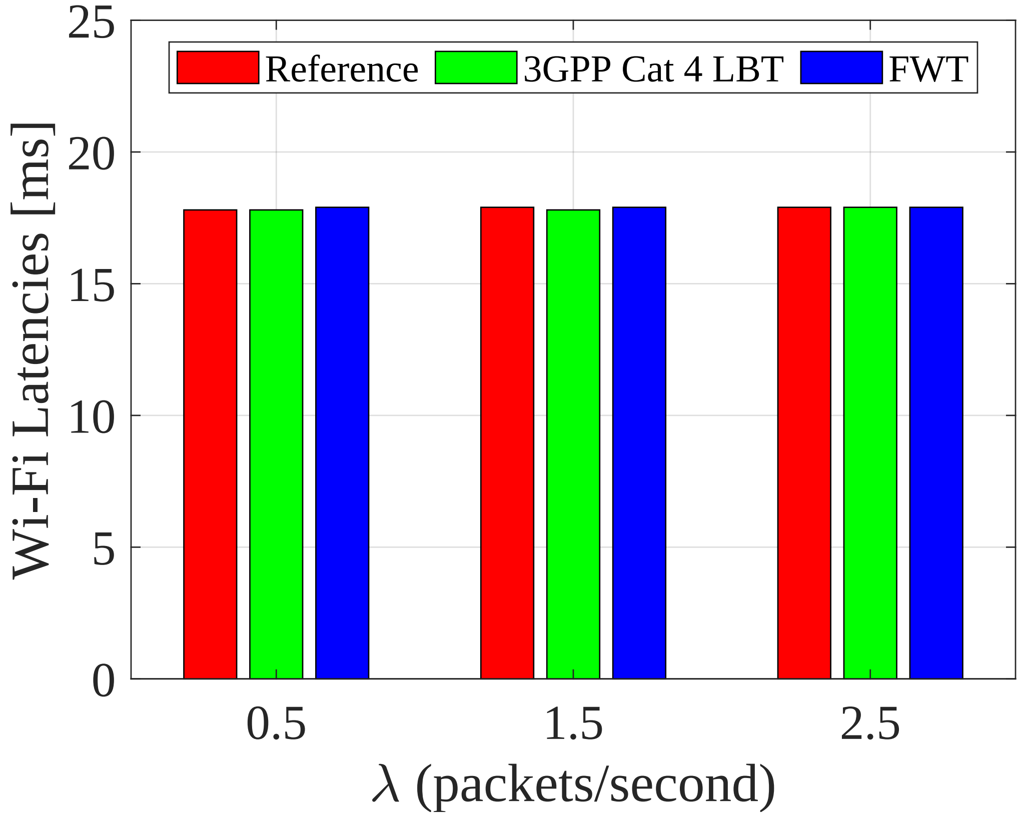


Figure 4.13: Wi-Fi latency performance of the proposed FWT method.

performance improvements for the existing Wi-Fi network provided by the FWT method (as observed in Fig. 4.12) are not obtained at the expense of the LTE-LAA throughput performance, which is comparable under medium and higher traffic loads (λ = 1.5 and 2.5 packets/second) and even better at lower traffic loads (λ = 0.5 packets/second). As a result, the total aggregated throughput of both networks is significantly enhanced as it can be appreciated in Fig. 4.15, which shows very significant throughput performance improvements with respect to the 3GPP Cat 4 LBT algorithm of 39.2% (41.1 Mbps), 13% (11.6 Mbps) and 6.5% (5.2 Mbps) for λ = 0.5, 1.5 and 2.5 packets/second, respectively. These improvements are larger than those observed for the dynamic and static CW methods analysed in the previous sections and can be explained by the ability of FWT to select an adequate waiting time, which ultimately results in a reduced number of collisions between both coexisting networks and consequently in an improved performance for both networks,

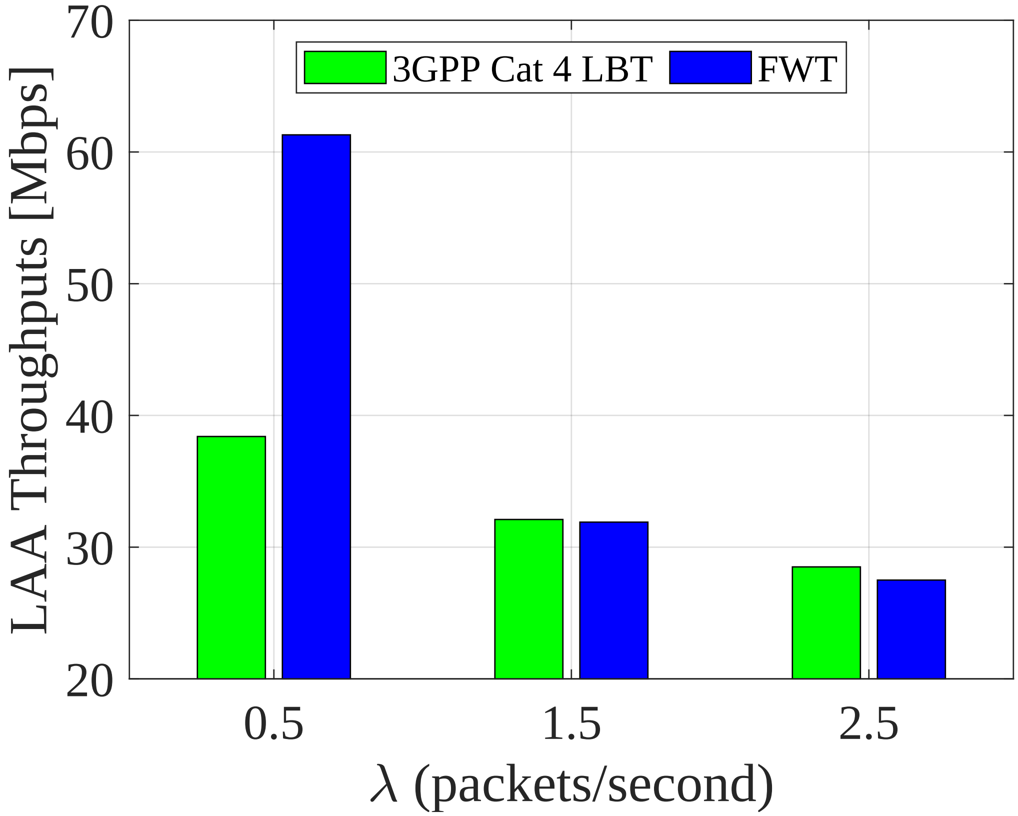


Figure 4.14: LTE-LAA throughput performance of the proposed FWT method.

thus making the proposed FWT method a more suitable candidate for LTE-LAA.

4.8.4 Variants of the Proposed Waiting Time Adaptation Methods

The performance of LTE-LAA and Wi-Fi networks is here analysed when the minimum and mode variants of the proposed waiting time adaptation methods are considered. Fig. 4.16 shows the throughput of the existing Wi-Fi network under different traffic loads for all the waiting time adaption methods considered in this chapter, including the 3GPP Cat 4 LBT and proposed methods, both in their standard versions and with the minimum and mode variants. It can be noticed that the minimum variants either provide a similar Wi-Fi throughput performance as the original versions of the respective method or, in some cases, lead to a slight throughput performance degradation, but in no case the minimum

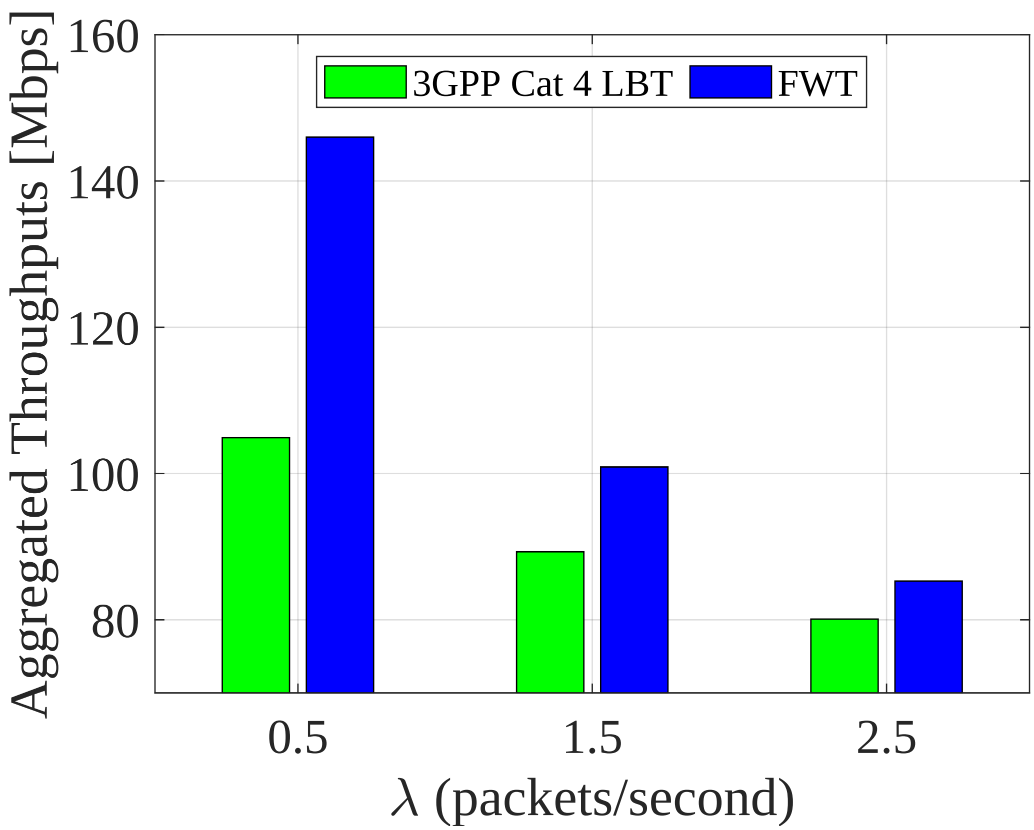


Figure 4.15: Aggregated throughput performance of the proposed FWT method.

variants lead to a throughput performance improvement in the Wi-Fi network. These results indicate that the minimum variants are not suitable for a fair coexistence of the LTE-LAA network with the existing Wi-Fi network. The mode variants lead in most cases to higher Wi-Fi throughputs than their minimum counterparts, however they do not necessarily perform better than the standard versions of their respective methods (if fact, the mode variant leads to a higher throughput for all traffic loads only for the 3GPP Cat 4 LBT and DynCW-2 methods). As it can be observed in Fig. 4.16, the best Wi-Fi throughput performance for all traffic loads is attained with the FWT method in its standard version.

Fig. 4.17 presents the latencies of the considered methods and their variants under different traffic loads. As it can be appreciated, and in line with the latency performance results presented in previous sections, comparable latencies are obtained with all methods

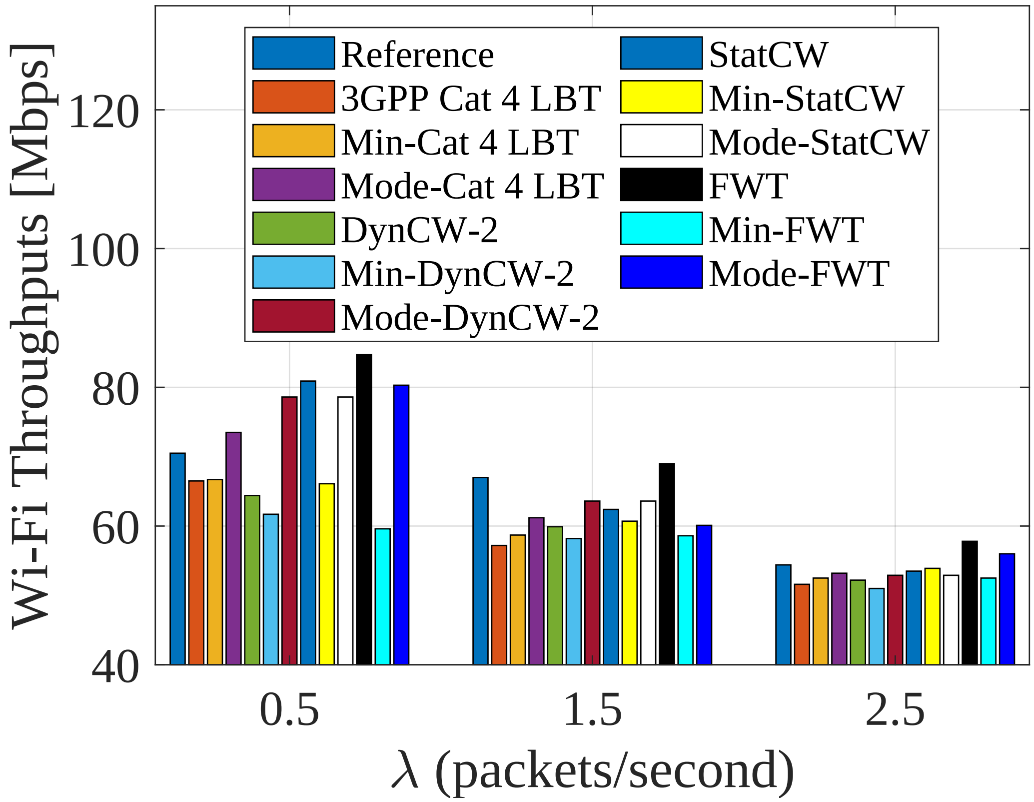


Figure 4.16: Wi-Fi throughput performance of the proposed methods and their variants.

and for all traffic loads.

Fig. 4.18 presents the LTE-LAA throughput performance attained by the various methods and variants under different traffic loads. The performances observed in this figure can largely be explained based on the trends discussed for the Wi-Fi throughput performance in Fig. 4.16, noting the existence of a performance trade-off between the Wi-Fi and LTE-LAA networks such that an increase in the Wi-Fi throughput can usually be associated with a corresponding decrease in the LTE-LAA throughput and vice versa.

The aggregated throughput performances of both Wi-Fi and LTE-LAA networks for the various methods considered in this chapter and their variants are shown in Fig. 4.19. As in previous figures, there are some specific cases where one of the variants provides a better performance than the original version of the corresponding method, however there is no clear trend that can guarantee an improved performance in all cases when a variant

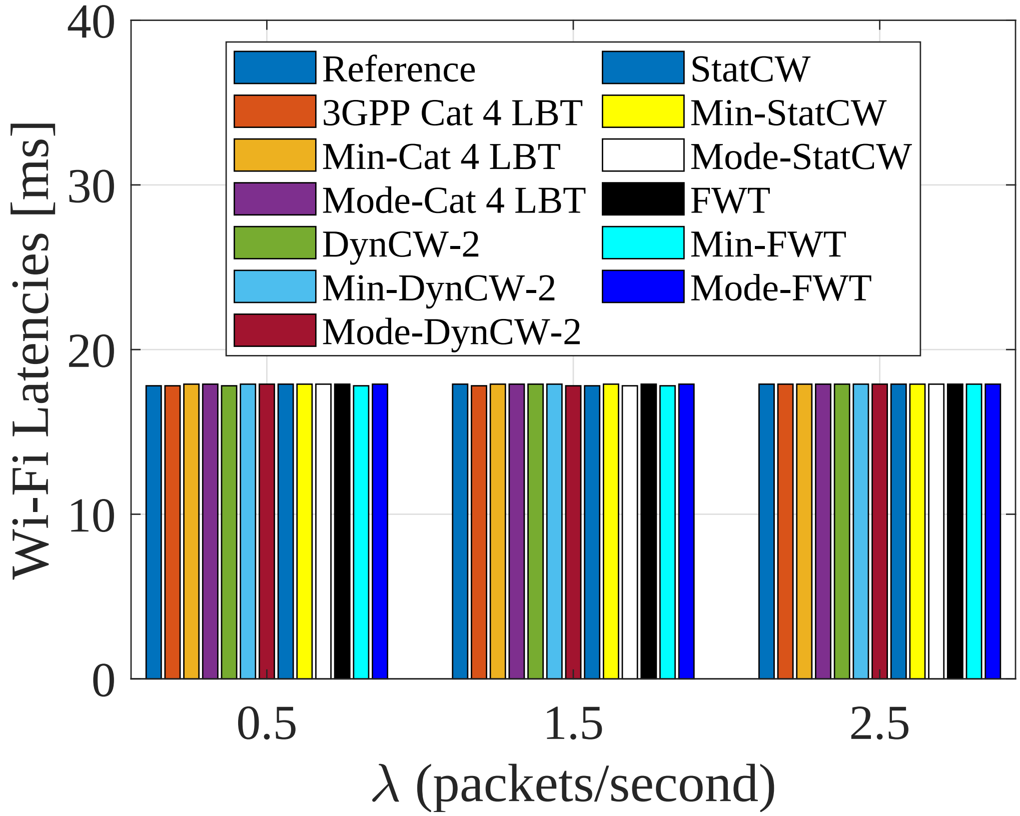


Figure 4.17: Wi-Fi latency performance of the proposed methods and their variants.

is employed.

When jointly taking into account all the methods considered in this chapter to select/adapt the waiting times of LTE-LAA and their variants, it becomes apparent that the FWT method (in its standard version) is the most suitable candidate. On the one hand, the FWT method is the only candidate that in all cases (i.e., all traffic loads) ensures that the Wi-Fi throughput performance will not be degraded (with respect to the reference case) by the introduction of an LTE-LAA network, and therefore leads to a fair coexistence. As a matter of fact, and interestingly, the introduction of an LTE-LAA network using the proposed FWT method results indeed in a higher throughput performance for the existing Wi-Fi network than the introduction of another Wi-Fi network, as observed in Fig. 4.16. On the other hand, the FWT method yields the highest aggregated throughput between both networks. Therefore, the proposed FWT method is the only method out

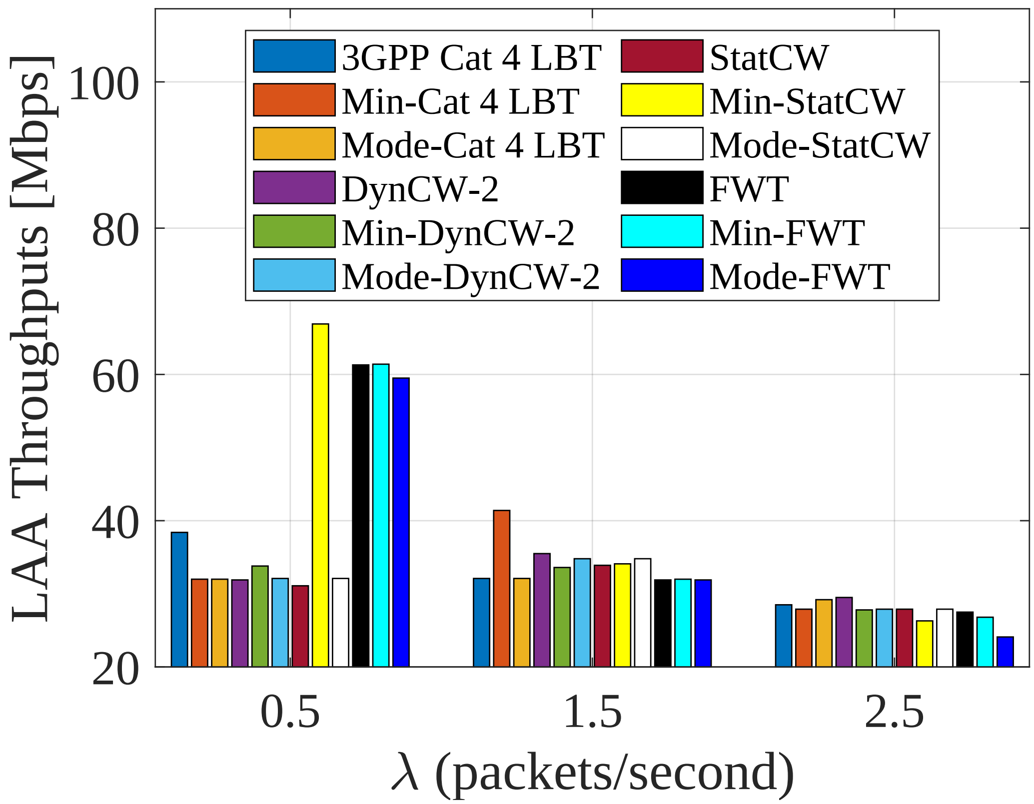


Figure 4.18: LTE-LAA throughput performance of the proposed methods and their variants.

of all the methods considered in this chapter (including the 3GPP Cat 4 LBT method) that guarantees a fair coexistence with the existing Wi-Fi network (and in fact improves its performance) while at the same time providing the highest aggregated throughput between both networks.

4.8.5 LTE Transmission Times Adaptation Method

The performance of LTE-LAA and Wi-Fi networks is investigated here using the proposed dynamic TxOP period method. Fig. 4.20 depicts the throughputs for the existing Wi-Fi network under different traffic loads for the homogeneous coexistence (i.e., Wi-Fi and Wi-Fi) and the heterogeneous coexistence (i.e., Wi-Fi and LTE-LAA) scenarios. In particular,

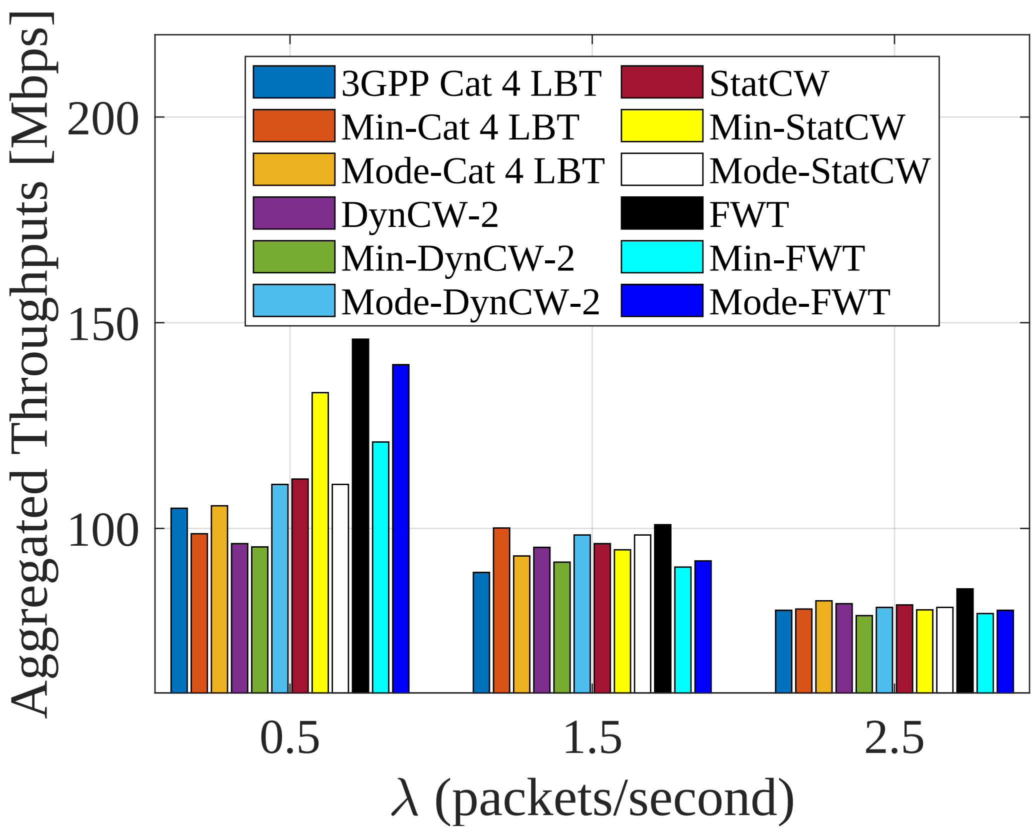


Figure 4.19: Aggregated throughput performance of the proposed methods and their variants.

the 3GPP Cat 4 LBT method with various static TxOP periods is considered for Wi-Fi/LAA coexistence. Moreover, the proposed dynamic TxOP approach is investigated for the Wi-Fi/LAA coexistence scenario as well. It can be seen that the standard Cat 4 LBT method achieves lower Wi-Fi throughputs compared to the reference case for the different static TxOP periods for all traffic loads. The proposed dynamic TxOP method, when compared to the static TxOP method, provides a comparable Wi-Fi throughput performance for $\lambda = 1.5$ and 2.5 packets/second, and a slightly better throughput for $\lambda = 0.5$ packets/second, which in all cases is lower than the throughput experienced by the Wi-Fi network in the reference case. These results indicate that the proposed dynamic TxOP method does not provide in general an improved fairness for the existing Wi-Fi network.

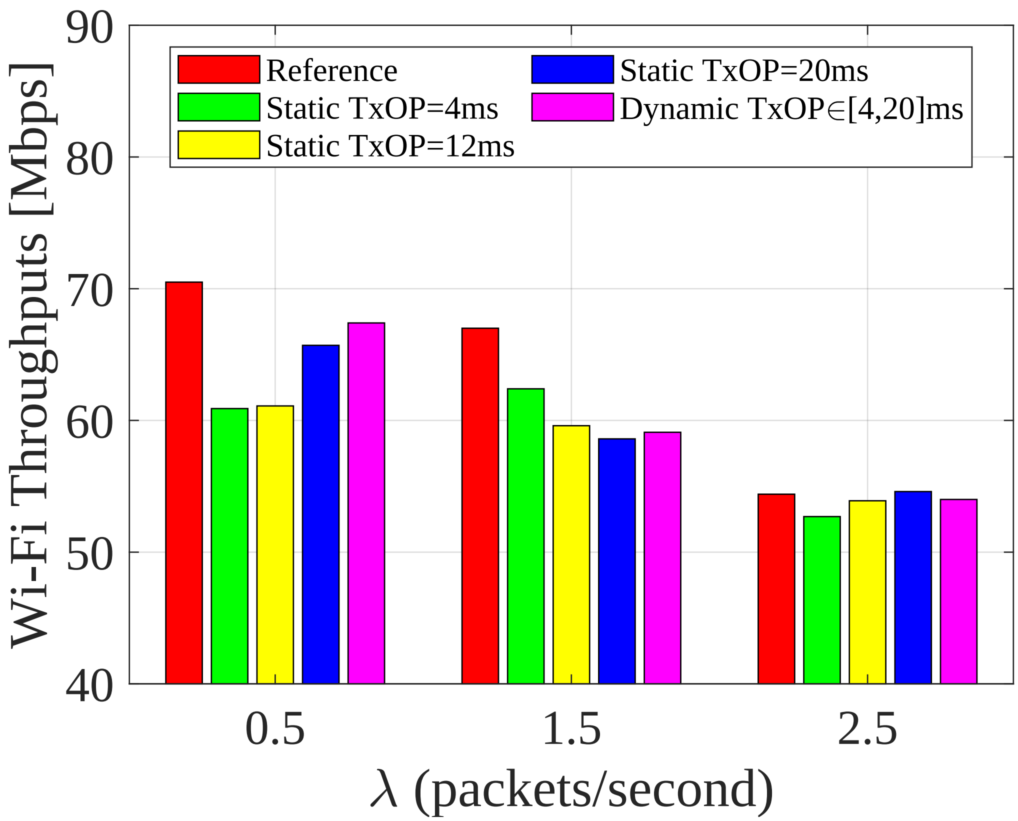


Figure 4.20: Wi-Fi throughput performance of the proposed dynamic TxOP period method.

The corresponding latencies for the existing Wi-Fi network are depicted in Fig. 4.21. It can be noticed that all methods achieve very similar performance in terms of Wi-Fi latency. As a result, the Cat 4 LBT method using a static TxOP approach and the proposed dynamic TxOP method do not degrade the existing Wi-Fi latency.

Fig. 4.22 presents the LAA throughput performance for the Wi-Fi/LAA coexistence scenario using the static approach of Cat 4 LBT and using the proposed dynamic TxOP approach. For low traffic loads (λ = 0.5 packets/second), it can be noticed that the dynamic TxOP method provides the same throughput as the static TxOP method with a 20 ms TxOP. This can be explained by the fact that, under low traffic loads, the channel is sparsely used, long idle times are frequent and collisions are unlikely to occur. As a result, the vast majority of transmissions are performed with the lowest value of the CW

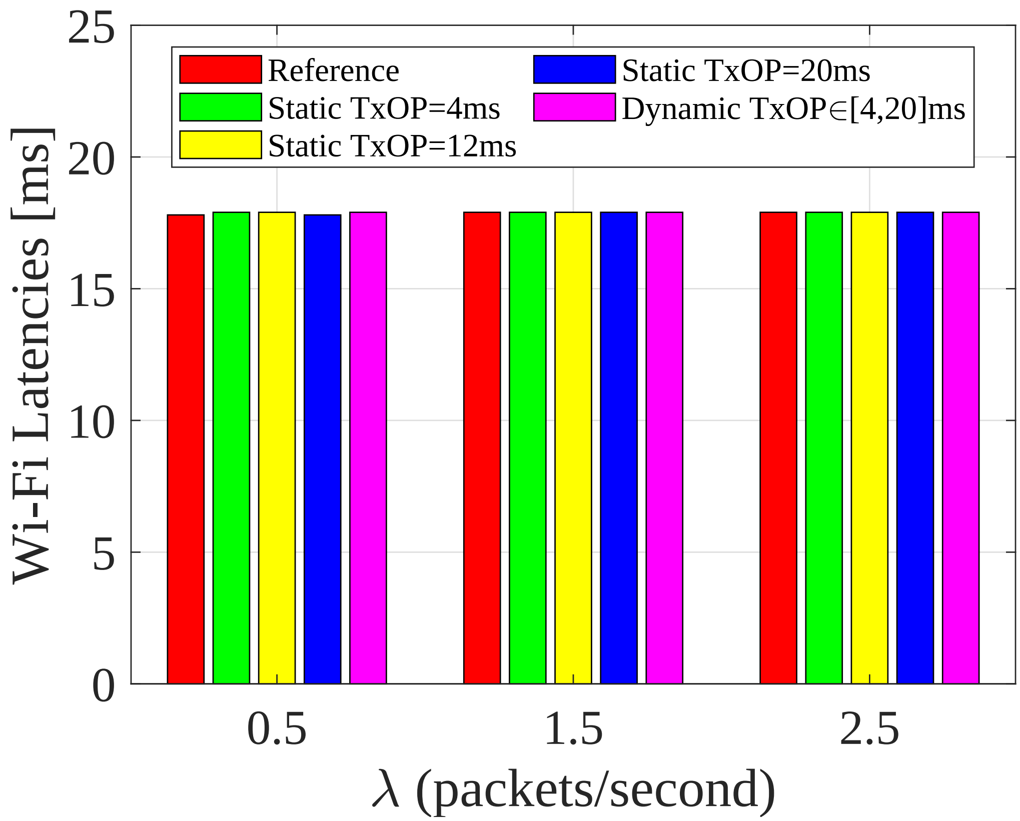


Figure 4.21: Wi-Fi latency performance of the proposed dynamic TxOP period method.

(i.e., 15) and therefore most of the time the dynamic TxOP method selects the highest TxOP available (i.e., 20 ms as illustrated in Table 4.5). In this scenario of low traffic load (λ = 0.5 packets/second), the dynamic TxOP method is equivalent to the static TxOP method with a 20 ms TxOP and, as a result, both methods achieve the same throughput. Notice that the achieved throughput is the highest attained for λ = 0.5 packets/second, which indicates that a constant selection of a 20 ms TxOP in such a case is the optimum choice when it comes to the LTE throughput.

For medium traffic loads (λ = 1.5 packets/second), Fig. 4.22 shows that the static TxOP method is unable to achieve the same throughput as the proposed dynamic TxOP method. This is because under this higher traffic load, the channel usage increases and so does the number of collisions. As a result, a constant 20 ms TxOP is not the optimum choice anymore since this long transmission time will lead to more frequent collisions and therefore a lower throughput (this is also suggested by the fact that, under a static TxOP, the same throughput is obtained for 12 ms and 20 ms TxOP, showing that there is no benefit from performing longer transmissions). In this scenario, and as a result of the presence of some collisions in the channel, the CW will be increased sometimes from the lowest value (i.e., 15) to the next value (i.e., 31) and, when this occurs, the proposed dynamic TxOP method will accordingly reduce the TxOP from 20 ms to 4 ms in order to reduce the likelihood of more frequent channel collisions. As appreciated in Fig. 4.22, this dynamic adaption of the TxOP performs well and leads to a higher throughput for the LTE-LAA network than any of the static configurations. This is also confirmed for higher traffic loads (λ = 2.5 packets/second), where it can be clearly appreciated that the proposed dynamic TxOP yields a significantly improved throughput performance as a result of this smart adaption of the TxOP length to the instantaneous occupancy activity in the Wi-Fi channel.

The total aggregated throughputs for the coexisting networks (i.e., Wi-Fi and LTE-LAA) for the various methods under different traffic loads are depicted in Fig. 4.23. The results presented in Fig. 4.23 show not only that the proposed dynamic TxOP method provides the highest aggregated throughput for all traffic loads compared to the standard Cat 4 LBT method based on a static TxOP configuration, but also obtains more significant performance improvements with respect to the static TxOP method as the traffic load increases. Specifically, the performance improvement in the total aggregated throughputs for both networks using the dynamic TxOP method compared to the static TxOP method for $\lambda = 2.5$ packets/second is 60.1% (42.2 Mbps), 34.8% (29 Mbps) and 15.8% (15.3 Mbps) for a static TxOP period of 4, 12 and 20 ms, respectively.

4.8.6 Discussion

The methods proposed in this chapter fall into two categories, namely those focused on the LTE-LAA waiting times and those focused on the LTE-LAA transmission times. For the first category, the results presented in Section 4.8.4 concluded that the FWT method is the most convenient approach within its category since it is the only method out of all the methods considered in this chapter (including the 3GPP Cat 4 LBT method) that guarantees a fair coexistence with the existing Wi-Fi network (i.e., it does not produce a degradation more significant than that caused by another Wi-Fi network) while at the same time provides the highest aggregated throughput between both networks when compared

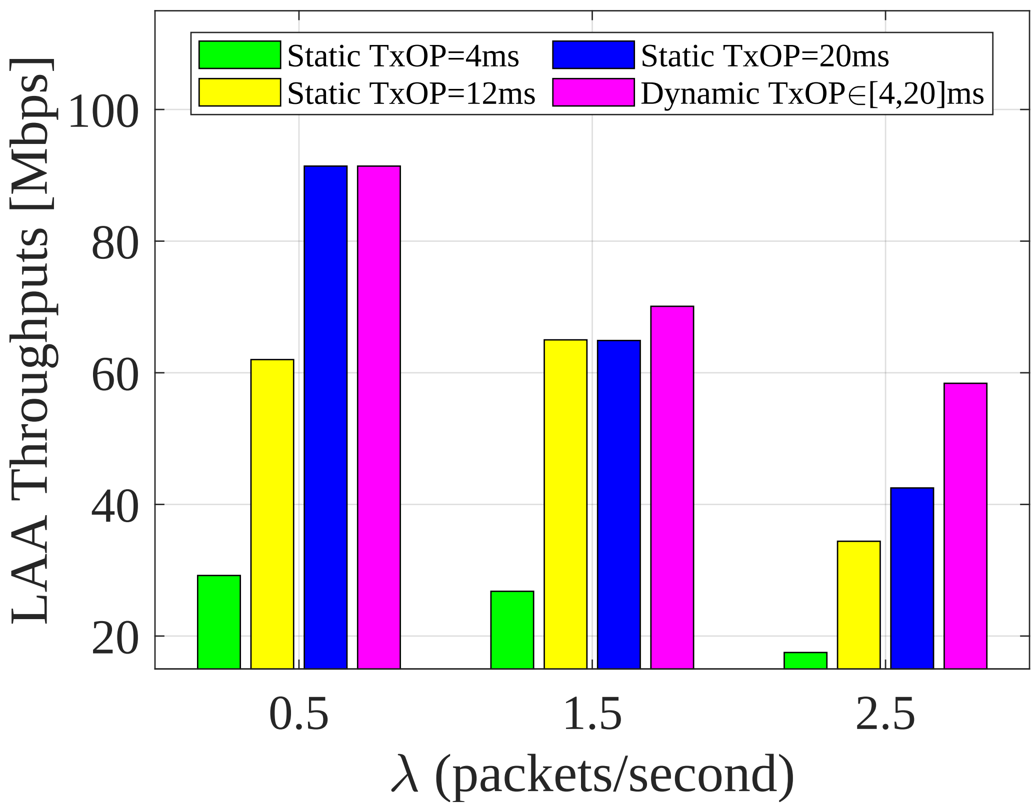


Figure 4.22: LTE-LAA throughput performance of the proposed dynamic TxOP period method.

to the rest of methods in the same category. For the second category, a method has been proposed based on the dynamic adaption of the TxOP length, which is unable to improve the fairness offered by the 3GPP Cat 4 LBT method but yields a higher aggregated throughput between both networks, in particular as a result of a significantly enhanced throughput for the LTE-LAA network.

Following the performance evaluation carried out individually for the methods in each category, a natural question is which of these methods would be more convenient in a practical coexistence scenario. This question can be answered based on the Wi-Fi throughput results shown in Fig. 4.24 and the total aggregated throughputs shown in Fig. 4.25, which compare together the main results shown in previous sections. As it can be appreciated, the FWT method is the only method that can fully meet the fairness requirement as de-

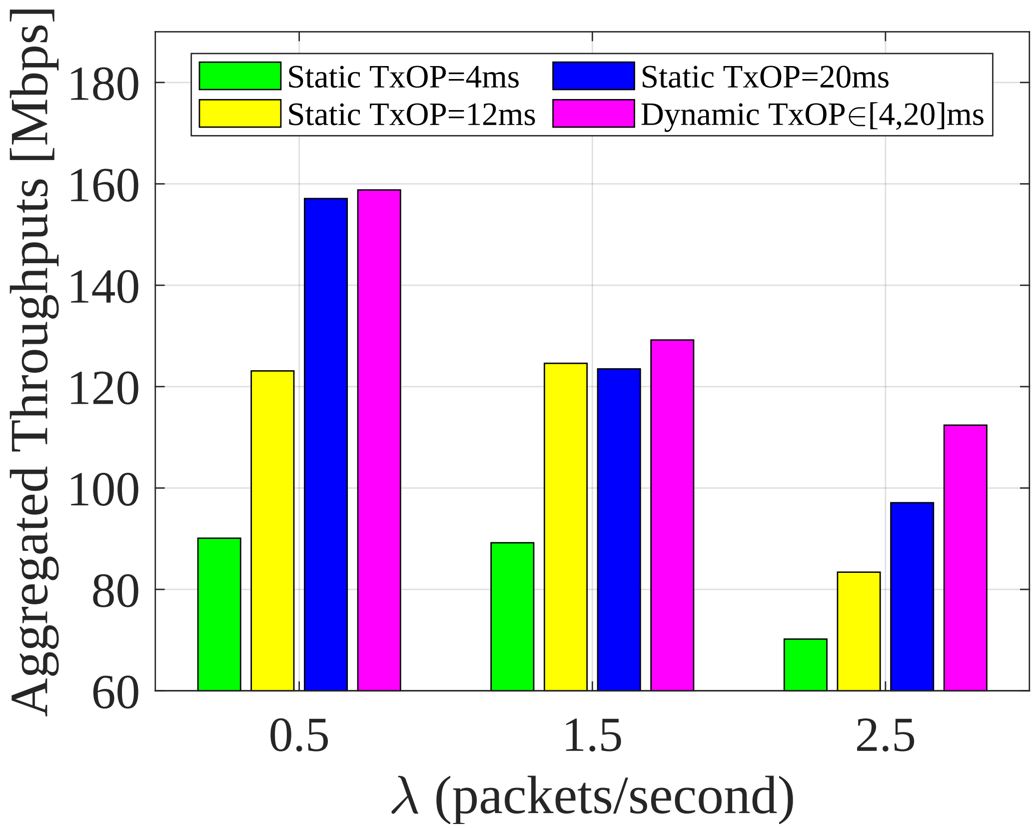


Figure 4.23: Aggregated throughput performance of the proposed dynamic TxOP period method.

fined by the 3GPP. Thus, this method may be more appealing to scenarios where the Wi-Fi and LTE-LAA networks are owned by different operators, where the LTE-LAA operator is strictly required to avoid causing unacceptable performance degradation to the Wi-Fi operator. On the other hand, the dynamic TxOP method provides the highest aggregated throughput at the expense of a slightly degraded Wi-Fi throughput and thus it may be more suitable to scenarios where both networks are owned by the same operator, for example where a mobile cellular operator offers Wi-Fi hotspots to its clients and therefore the ultimate interest is in maximising the overall aggregated throughput (i.e., the total capacity) of the owned network infrastructure.

Finally, it is worth noting that, while in this chapter the traffic load has been varied by modifying the packet inter-arrival rates at the application layer ($\lambda = 0.5$, 1.5 and 2.5

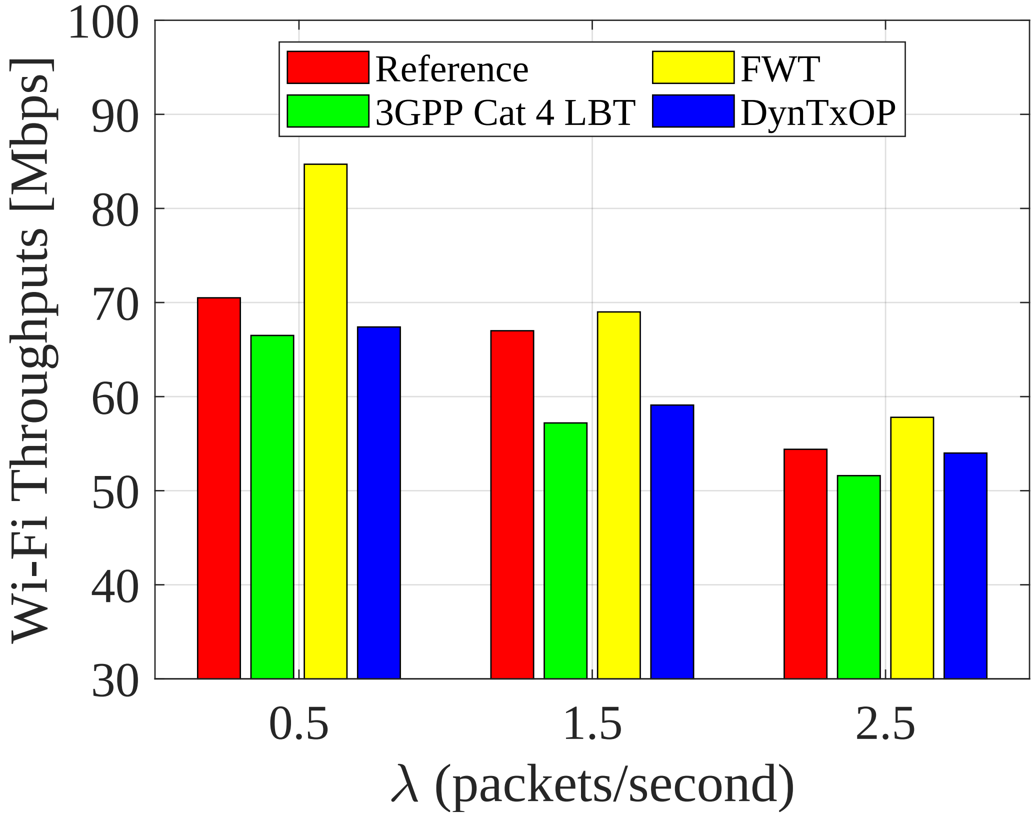


Figure 4.24: Wi-Fi throughput performance of selected methods (5 STAs/UEs per AP/eNB).

packets/second), this can also vary based on the network scale (i.e., number of Wi-Fi APs, LTE-LAA eNBs, users). While the numerical results may change for different network conditions, the main conclusions of this study remain the same. In order to illustrate this, Figs. 4.26 and 4.27 show the counterparts of Figs. 4.24 and 4.25 when the total number of users in the system is doubled. As it can be appreciated, the main conclusions discussed above for the methods proposed in this chapter are also valid under larger network scales.

4.9 Summary

Current studies aim to enable a fair coexistence between LTE-LAA and Wi-Fi networks over unlicensed spectrum bands. The current 3GPP Cat 4 LBT algorithm does not per-

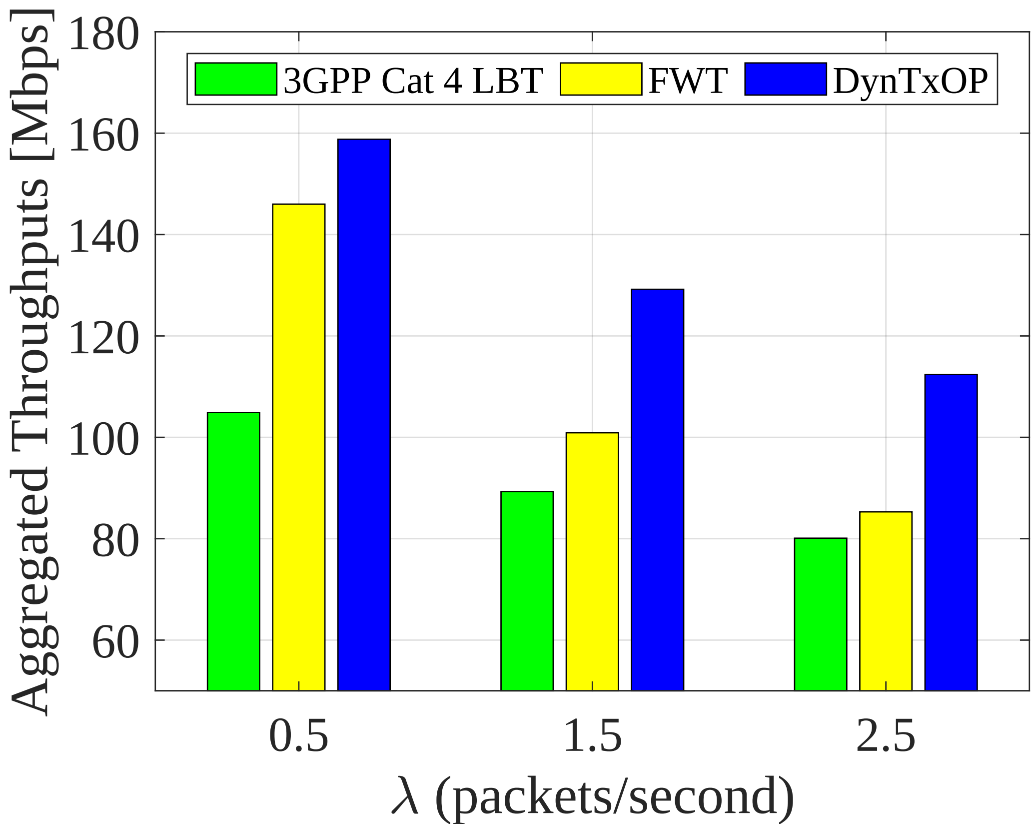


Figure 4.25: Aggregated throughput performance of selected methods (5 STAs/UEs per AP/eNB).

fectly meet the fairness definition given by 3GPP. In particular, a Wi-Fi throughput degradation can be noticed due to deploying LTE-LAA with Wi-Fi over the same unlicensed band. Different design parameters of the LBT algorithm play a key role in this heterogeneous coexistence such as the waiting and transmission times for LAA. Therefore, in this chapter, novel methods have been proposed to tune the waiting and transmission times for LAA as an alternative to the traditional contention window-based approach and the fixed configuration of the TxOP period for LAA proposed by the 3GPP. The obtained simulation results have shown that, for LAA/Wi-Fi coexistence, selecting fixed waiting times for LAA based on the knowledge of the activity statistics of the existing Wi-Fi network achieves better performance compared to the contention window-based approach of the standard 3GPP Cat 4 LBT algorithm, and moreover it also results in less complex coexistence

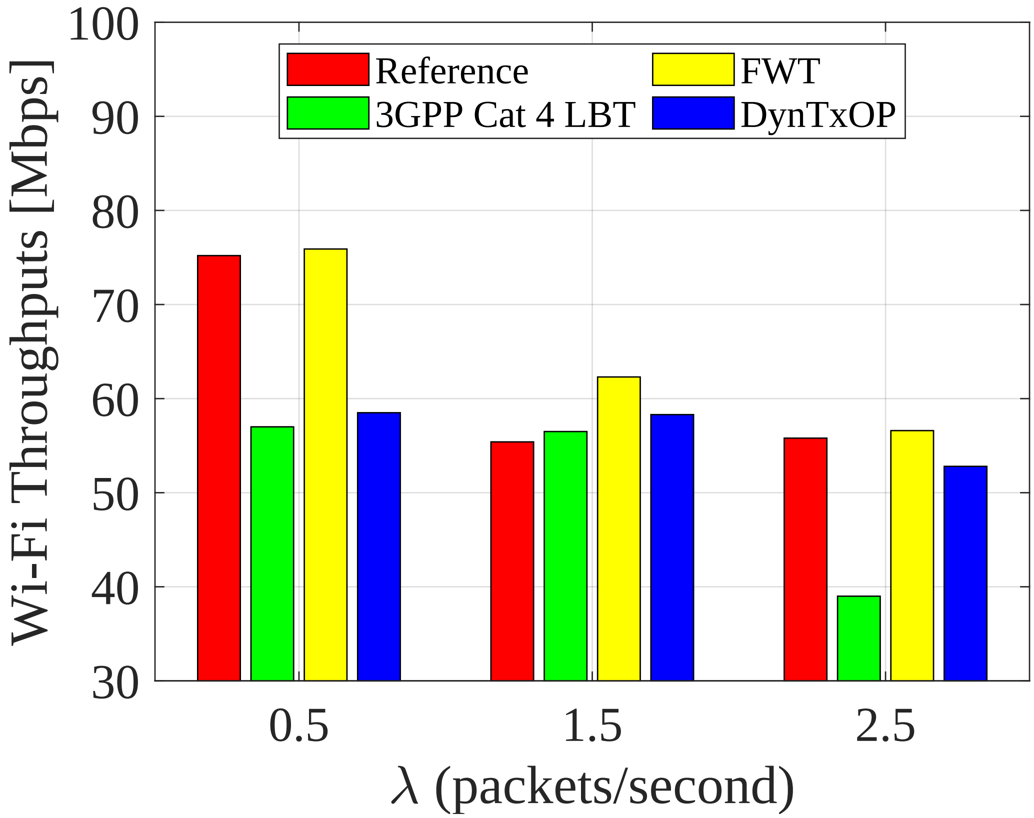


Figure 4.26: Wi-Fi throughput performance of selected methods (10 STAs/UEs per AP/eNB).

mechanisms. In addition, the dynamic TxOP period method achieves better performance compared to the fixed TxOP period approach of the standard Cat 4 LBT algorithm. The most convenient method to use depends on the particular business scenario and target of the network operator as discussed in this chapter but, in any case, the proposed methods can provide significant performance improvements compared to the standard 3GPP Cat 4 LBT method.

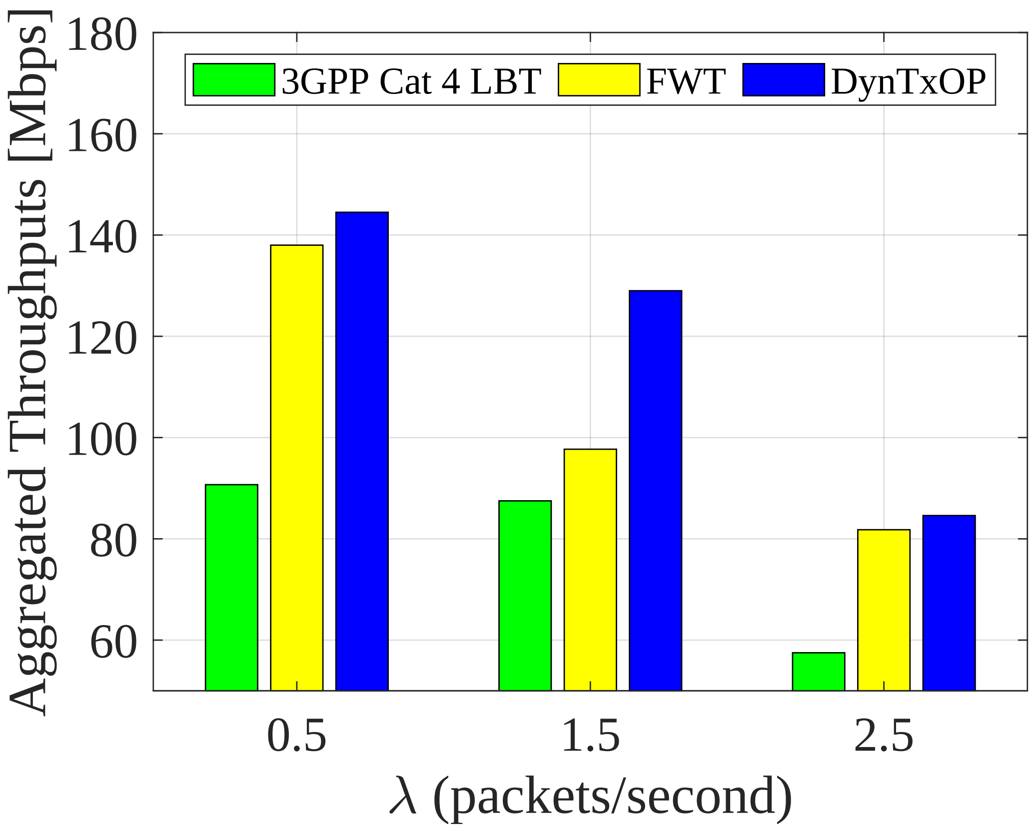


Figure 4.27: Aggregated throughput performance of selected methods (10 STAs/UEs per AP/eNB).

Chapter 5

Conclusions and Future Work

5.1 Contributions

Mobile network operators have recently faced a huge service challenge as data traffic increases due to the spectacular usage of mobile devices. As a result, mobile operators have utilised the concept of spectrum sharing as a key solution enabling mobile access to additional unlicensed bands (specifically 5 GHz band) when other services are not using them. These free unlicensed bands are mainly occupied by Wi-Fi technology and the use of these unlicensed bands for mobile network services without a controlled deployment could lead to a performance degradation for the existing technology (i.e., Wi-Fi). Therefore, the 3GPP standardised LTE-U and LAA technologies to allow a fair coexistence between mobile and Wi-Fi networks and not significantly degrading the performance of Wi-Fi networks. In this sense, this dissertation has presented novel improvements to the 3GPP coexistence mechanisms by exploiting the knowledge of the existing Wi-Fi activity statistics to achieve a fair coexistence. Various parameters of the coexisting protocol such as duty cycle, contention window boundaries and transmission opportunity times have been tuned based on this knowledge. It is worth mentioning that deploying mobile networks in unlicensed bands was introduced firstly in the context of the 4G LTE technology but it is also considered in the context of 5G New Radio in Unlicensed bands (5G NR-U). Moreover, the main focus of this research is on the MAC LBT protocol which is almost the same in 5G network, and therefore the main conclusions and findings of this research should still be applicable in the context of 5G NR-U operating in the 5 GHz and higher unlicensed bands.

An exhaustive comparison between LTE-U and LTE-LAA (Category 4 LBT) technologies have been provided in this thesis using the discrete event simulator ns-3 when they are deployed with Wi-Fi in the unlicensed 5 GHz band. In addition, the impact of changing several key parameters has been investigated as well.

Finally, the study performed for LTE-LAA/Wi-Fi coexistence has contributed a set of novel methods that describe different design parameters of the LBT algorithm such as the waiting and transmission times for LAA that would be tuned/selected based on the knowledge of the existing Wi-Fi activities to improve the 3GPP Category 4 LBT algorithm leading to a more fair coexistence. Various novel methods have been proposed to tune the waiting and transmission times for LAA instead of the traditional contention window-based approach and the fixed configuration of the TxOP period for LAA proposed by the 3GPP.

5.2 Findings and Conclusions

The outcome of the comprehensive study between LTE-U and LTE-LAA (Category 4 LBT) technologies has highlighted two key aspects. Firstly, LTE-LAA can enable a more fair coexistence in terms of throughput and latency than LTE-U technology. Secondly, several key parameters in LTE need modifications to provide more fairness for this coexistence.

The proposed approach for LTE-U Wi-Fi coexistence has been validated using the ns-3 simulator, demonstrating that the proposed methods can provide a significant improvement in the capacity available to LTE-U at no cost compared to the current LTE-U approach with dynamic duty cycle.

The outcome of the proposed methods for LTE-LAA/Wi-Fi coexistence has highlighted two key aspects. Firstly, selecting fixed waiting times for LAA based on the knowledge of Wi-Fi activities is more friendly to the existing Wi-Fi and provides better total aggregated throughput for both coexisting networks with less complex coexistence mechanisms compared to the current 3GPP algorithm (i.e., Cat 4 LBT). Secondly, the novel dynamic TxOP approach is more friendly to the existing Wi-Fi and provides better total aggregated throughput for both coexisting networks compared to the current 3GPP algorithm (i.e., Cat 4 LBT) which considers a fixed TxOP period approach.

In summary, the novel contributions presented in this thesis for both LTE-U and LTE-LAA have demonstrated the possibility to improve not only the coexistence fairness between mobile and Wi-Fi networks in unlicensed bands compared to the standard 3GPP method but also to provide noticeable throughput improvements, thus allowing both networks to coexist in a fair manner and enjoy an improved network capacity.

5.3 Future Work

The research conducted in this dissertation opens new ideas for future works. Some possible directions to extend the studies performed in this dissertation are discussed below.

There are still other approaches that can be considered to improve the coexistence between mobile and Wi-Fi networks over unlicensed bands in more realistic conditions. Firstly, the impact of errors in spectrum sensing when the channel is sensed could be investigated. In particular, investigating the impact of the imperfect Cumulative Distribution Function (CDF) for the ON time periods for the existing Wi-Fi network on the proposed methods. It is worth mentioning that the CDF that has been provided in this research is under perfect sensing conditions and this could affect the accuracy of the estimated CDF. In the standard 3GPP Cat 4 LBT method, this would affect by means of interference, but in case of the proposed methods, which are configured based on the CDF of Wi-Fi ON periods, this would also affect the configuration of the contention window and the TxOP period since they would be based on an incorrectly estimated CDF. Thus, to assess the validity of the proposed methods under imperfect sensing conditions, different detection and false alarms can be added to investigate the imperfect sensing for the ON time periods for the Wi-Fi on the proposed methods [166]. Secondly, investigating another variant to the existing 3GPP Category 4 LBT method such as Energy Detection (ED) threshold for LTE. A dynamic ED threshold algorithm based on the knowledge of the existing Wi-Fi activity statistics could be proposed to provide a more fair coexistence mechanism. The materialisation of this idea into a specific algorithm and its performance evaluation is proposed as future work.

Another important aspect that can be considered to extend this research is the evaluation of the proposed methods in the context of 5G NR-U. The methods in this research have been evaluated in the context of the 4G LTE technology since at the time this research started, 5G was still an immature technology under development but the same principles are still applicable for 5G NR-U networks. This idea would be an interesting topic to be explored due to the difference between LAA in LTE and LAA in 5G NR-U networks. In particular, LTE is based on a time frame structure where every frame has 1-ms and the channel access has to be at the beginning of every 1-ms frame. On the other hand, in Wi-Fi technology, there is no time frame structure where every Wi-Fi node can start the transmission after sensing the channel to be idle for a certain time period by following its own channel access mechanism. As a result, while coexisting LTE with Wi-Fi in unlicensed band, LTE cannot start transmission until the beginning of its next 1-ms frame. For example, if the channel is free, LTE should wait until the beginning of the next frame and a reservation signal method is followed by transmitting a dummy signal that has no information to keep the channel busy and to prevent other Wi-Fi nodes from accessing the channel. This channel access mechanism followed by LTE would waste the spectrum in the case where the transmission of LTE is ready to start at any point other than the beginning of a frame. On the other hand, in 5G NR-U, this synchronization problem is solved by using flexible numerology where a dynamic adjustment for the number of sub-carriers and the duration of mini-slots is possible. In particular, the channel access scheduling in LAA of 5G NR-U can decrease the slot duration from 1-ms down to 125 μs [168]. This means that the dummy signal transmission is not needed to reserve the channel and this would be achieved by following the gap based access mechanism which allows the contention process to start at the right time. Therefore, if the channel is free, the transmission process can start in the next frame without any need to waste time of the remaining 1-ms by a dummy signal as in LTE-LAA. It can be noticed that the spectrum is used more efficiently for LAA in 5G NR-U compared to LTE and this is the main difference. However, the proposed methods in this research are applicable for LAA in 5G NR-U as well and the only difference is the channel access procedure in the PHY layer while the MAC specifications are almost the same. In particular, the reservation signal used by LAA in LTE needs to be taken into account and this may affect the actual contention process and the efficiency of the proposed methods. This reason clarifies why it could be interesting to investigate the performance of the proposed methods in the context of 5G NR-U technology.

Finally, another aspect that can be explored as a future work is the use of Artificial Intelligence (AI) and reinforcement learning techniques for the coexistence between mobile and Wi-Fi networks over unlicensed bands. A few key ideas have been discussed during my research visit to the Centre Technolo'gic de Telecomunicacions de Catalunya (CTTC) in Spain regarding this topic. In particular, neural networks and Q-learning techniques could be used in order to select/adapt the various key design parameters for LAA utilising the knowledge of the activity statistics of Wi-Fi network.

5.4 Summary

In this thesis, various methods are investigated to improve the coexistence between mobile and Wi-Fi networks in unlicensed spectrum bands based on the Wi-Fi activity statistics. In particular, the Wi-Fi activity statistics are exploited in order to achieve a fair coexistence between mobile and Wi-Fi networks in unlicensed bands. Based on the provided results, it has been shown that implementing the proposed methods with the smart exploitation of the knowledge of Wi-Fi activity statistics can guarantee a fair coexistence between mobile and Wi-Fi networks. Moreover, for some cases, the proposed methods can improve the performance of Wi-Fi network compared to the homogeneous coexistence scenario between Wi-Fi networks only.

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