LTE IN UNLICENSED BANDS: A RIVAL OR COLLABORATOR TO WI-FI?

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DECLARATION

I hereby, declare that this manuscript, entitled *“LTE in Unlicensed Bands: A Rival or Collaborator to Wi-Fi?”,* is the result of my own work except for quotations and citations which have been duly acknowledged.
I also declare that, to the best of my knowledge and belief, it has not been previously or concurrently submitted, in whole or in part, for any other degree or diploma at Nazarbayev University or any other national or international institution.

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List of Abbreviations

AP – Access Point
CA – Carrier Aggregation
CC - Component Carrier
CCA - Clear Channel Assessment
COT – Channel Occupation Time
CSMA/CA – Carrier Sense Multiple Access with Collision Avoidance
CTS – Clear-to-Send
CW – Contention Window
DCF – Distributed Coordination Function
DL – Downlink
DTX – Discontinuous Transmission
eCCA – Extended Clear Channel Assessment
eNB – Evolved NodeB
FBE – Frame Based Equipment
FFP - Fixed Frame Period
LAA – Licensed Assisted Access
LBE – Load Based Equipment
LBT – Listen-Before-Talk
LTE – Long Term Evolution
MAC – Media Access Control
MCOT – Maximum Channel Occupancy Time
OFDM - Orthogonal Frequency Division Multiplexing
OFDMA – Orthogonal Frequency Division Multiple Access
QoS – Quality of Service
RAT – Radio Access Technology
RTS – Request-to-Send
SDL – Supplemental Downlink
SE - Spectral Efficiency
SINR – Signal-to-Interference-plus-Noise Ratio
STA - Station
TPC - Transmit Power Control
UE – User Equipment
UL - Uplink

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Abstract

Due to the rapidly increasing demand for internet traffic, mobile operators have faced a problem of bandwidth availability. Since only licensed spectrum has been previously utilized by wireless networks, moving LTE to the 5 GHz unlicensed bands has become a popular research initiative, known as LTE-Licensed Assisted Access (LTE-LAA).

This thesis studies the feasibility and implementation of LTE-LAA, and sets a goal of confirming the effectiveness of this technology. An alternative implementation of a *Listen-Before-Talk* channel contention mechanism is tested in this work with the use of LTE-A Vienna Link Level Simulator. The obtained results suggest that LTE-LAA is capable of boosting network throughput while providing harmonious coexistence with the IEEE 802.11 standard operating in the same unlicensed spectrum.

1. Thesis Overview

1.1 Introduction

Recent progress in mobile technologies has continuously been pushing the demand for internet traffic on mobile devices to new extents. Throughput requested by mobile users increases dramatically, and Ericsson expects that by 2021 there will be a more than 10 times increase in mobile throughput since 2015 [1]. This increasing trend has been observed in all major telecommunication markets worldwide, and has forced mobile operators to invest in costly methods of improving spectral efficiency (SE) of their networks and increasing available licensed bandwidth to allow serving more users at higher speeds. *Carrier Aggregation* [2] and *Heterogeneous Networks* [3] are examples of technologies that improve SE. However, these methods are still limited to the availability of bandwidth that mobile operators purchase from government agencies.

A new solution to the bandwidth scarcity problem that involves the use of unlicensed frequency bands for LTE operation has gained popularity in recent years. It was proposed that LTE operates in the 5 GHz unlicensed bands and shares this spectrum with different *Radio Access Technologies (RAT)*, including IEEE 802.11, i.e. Wi-Fi. The technology has been named *LTE-Unlicensed (LTE-U)* or *LTE-Licensed Assisted Access (LTE-LAA)* depending on the prioritization of fair spectrum sharing in a given geographical region. Since the RATs already occupying the 5 GHz spectrum could experience interference from LTE users, it has been required by most regulatory bodies that modifications are made to the LTE standard in order to guarantee the safety of Wi-Fi performance in the 5 GHz spectrum. Researchers have suggested numerous ways of LTE-LAA and LTE-U implementation, which also include various mechanisms of securing fair spectrum sharing. These efforts will play a significant role in the standardization of the final LTE-U and LTE-LAA protocols, which has been planned to be achieved in the next LTE releases. 3rd Generation Partnership Program (3GPP) and LTE-U Forum are the organizations responsible for the standardization of LTE-LAA and LTE-U respectively. Because LTE-LAA prioritizes fair spectrum sharing, more markets are expected to adopt this technology, hence, the focus of this work lies on implementation of LTE-LAA.

The current thesis is organized as follows: Differences in channel access schemes of LTE and other RATs as well as the challenges of LTE-U and LTE-LAA implementation are explained and discussed in detail in Section 2. Also, an overview of existing research in this area is included in this section. In Section 3, an alternative implementation of a fair spectrum sharing mechanism for LTE-LAA is proposed and evaluated using software simulation. Results obtained via the simulation are graphically presented and discussed in Section 4. Finally, concluding remarks are given in Section 5.

1.2 Objectives

The general objective of this thesis is to investigate the operation of LTE in unlicensed bands. Specifically, the goal of this work is to find confirmation that LTE-LAA can improve the mobile operator throughput without harming Wi-Fi performance.

2. Theoretical Background & Technical Literature Review

2.1 LTE in Unlicensed bands

A. Motivation for using unlicensed bands

Available licensed spectrum has become a scarce radio resource due to a tremendous rise in user requested data throughput. Bringing LTE to unlicensed bands presents a very attractive opportunity for mobile operators to offload traffic currently being utilized over licensed bands. In addition, acquiring rights to operate in a licensed band is very expensive for mobile operators due to limited spectrum and the exclusive use of a frequency band by a single operator. For instance, in 2015 AT&T spent more than $2.7 billion to acquire rights to solely utilize a total of 20 MHz of paired spectrum in 1700 MHz and 2100 MHz bands in New York City [4]. However, having available spectrum in free-to-use unlicensed bands would reduce the need to purchase more spectrum and potentially save telecommunication companies billions of dollars. Hence, researchers and mobile services providers have been strongly interested in the possibility of LTE operation in unlicensed bands.

B. Implemention Challenges

While being a very attractive solution to the bandwidth scarcity problem, moving the operation of LTE networks to the unlicensed spectrum is not a simple task. The 5 GHz unlicensed spectrum that is targeted by LTE service providers is already being used as a medium by other radio access technologies. This presents a potential interference problem. In addition, there exist regulations established by government agencies that limit the maximum allowed transmitted power and maximum channel occupation.

i. Since the 5 GHz unlicensed spectrum is available for use by different RATs, it has lately become increasingly popular among Wi-Fi equipment vendors. After the densely populated 2.4 GHz unlicensed spectrum became prone to co-channel interference with a widespread popularity of Wi-Fi stations (STA), the European Telecommunications Standards Institute (ETSI) has been making more and more 5 GHz bands available for IEEE 802.11 standard. In light of the emerging abundance of Wi-Fi STAs operating in the 5GHz bands, bringing LTE to these frequencies could harm Wi-Fi performance due to the incompatibility of these RATs as well as the co-channel interference caused by LTE.

The IEEE 802.11 standard is based on Orthogonal Frequency Division Multiplexing (OFDM). In OFDM, the transmitted waveform is spread over the entire channel bandwidth of up to 20 MHz. This bandwidth consists of multiple orthogonally spaced subcarriers. Subcarrier orthogonality eliminates the possibility of crosstalk, meaning neighboring subcarriers do not interfere with each other. Because Wi-Fi was designed to operate in unlicensed bands, a fair spectrum sharing mechanism was required in the MAC layer. As a result, Wi-Fi STAs take turns in having access to the channel during their allowed occupation times. There is no centralized controller since STAs can only access the channel at their need. This medium access scheme is called Distributed Coordination Function (DCF). DCF utilizes a mechanism called Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), which enables Wi-Fi STAs to first sense the interference levels in the medium before transmitting. In case of a busy channel detection a device backs off its transmission until the channel is accessible again. This essentially allows STAs to take turns using the frequency channel. In order to ensure fairness in granting access to one of multiple devices, DCF is backed up with a virtual carrier sensing method that reserves the channel for a certain STA by sending and receiving signals called Request to Send (RTS) and Clear to Send (CTS). This eliminates the possibility of packet collision when two devices sense an idle channel together and want to transmit simultaneously. Additional information about DCF can be found in [5].

Due to the QoS standards established by 3GPP, LTE utilizes Orthogonal Frequency Division Multiple Access (OFDMA), which is a modification of OFDM that enables the LTE scheduler to place distinct OFDM symbols dedicated to different users on separate orthogonal subcarriers. Unlike Wi-Fi, which occupies an entire channel for a shorter period of time, LTE dedicates portions of available bandwidth to multiple users for longer durations (Fig. 1). This allows for simultaneous transmission to multiple LTE UEs without intra-cell interference, which was not possible in Wi-Fi. Because of the utilized medium access scheme LTE does not require a contention based mechanism,

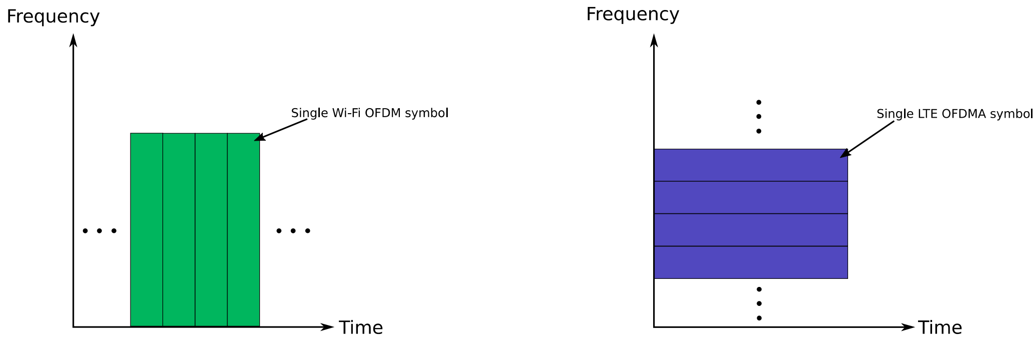

Figure 1. Resource Allocation in Wi-Fi (left) and LTE (right).

such as CMSA/CA. Instead, the single operator using a portion of licensed spectrum controls the medium and dynamically allocates radio resources to UEs based on the load and link conditions [6]. Thus, a fundamental difference between the MAC layers of Wi-Fi and LTE lies in the contention based channel access in Wi-Fi. This presents a danger for the prospect of bringing LTE to unlicensed bands since Wi-Fi STAs would continuously back off their transmission in the presence of interference from the LTE side and the entire channel would be taken up by LTE transmissions. In fact, the effects of LTE operating in the same band with Wi-Fi is studied in [7]. Authors simulated a scenario where multiple LTE eNodeB's and Wi-Fi APs share a 20 MHz wide unlicensed channel centered at 900 MHz. Results of the study showed that an unmodified LTE MAC protocol severely harms the Wi-Fi performance. While LTE only suffered an insignificant throughput loss of 3.85 % in the worst case, Wi-Fi throughput degradation ranged from 70% to 90% compared with the reference value obtained when Wi-Fi operated alone. Similar results were obtained in [8], where real hardware was used to show the effects that LTE has on Wi-Fi operating in the same channel.

ii. In addition to the coexistence problem, there are limitations set in some frequency bands. Depending on the country, different rules may apply to the unlicensed spectrum. For instance, in most European countries the mean Effective Isotropic Radiated Power (e.i.r.p) of the antennas operating in 5470-5725 MHz is limited to 27 dBm or 30 dBm in the case when Transmit Power Control (TPC) is present in a radiating device. TPC is a mechanism that mitigates the aggregate radiated power by at least 3 dBm when there is a large number of radiating devices [9]. In the 5150-5250 MHz band, TPC is not required, but these frequencies are only allowed for indoor use in Europe. More details about power restrictions in specific bands are available in [10]. In addition, 5250–5350 MHz and 5470–5725 MHz bands are often used by weather radars for meteorological purposes. This sets a limit onto RATs operating in these bands, as the latter have to avoid interference in the weather radar channel. In order to ensure the safety of the performance of weather radars, governments require RATs to implement a technique called Dynamic Frequency Selection (DFS), which periodically detects the level of interference and changes the operating channel to allow the weather radars to access it [9]. Regulatory bodies of different countries set different restrictions in the unlicensed bands, due to which the 5 GHz unlicensed spectrum has become highly fragmented [11]. These limitations have to be taken into account to enable LTE operation in unlicensed bands.

C. *Variants of LTE in unlicensed bands*

The differences in the requirements of operation in the unlicensed spectrum set by regulatory bodies of different countries have triggered development of variations of LTE in unlicensed bands. In regions like Europe and Japan, there is a regulation placed on unlicensed spectrum devices that requires support of the Listen-Before-Talk (LBT) mechanism. It is intended to provide means of fair spectrum sharing and coexistence between RATs utilizing the 5 GHz bands [12]. However, in the United States, China and South Korea there is no such requirement. Hence, two markets have emerged in these countries for the development of LTE in unlicensed bands - with and without LBT.

In the markets without the LBT requirement an approach called LTE-U was suggested. Qualcomm proposed three mechanisms that would ensure fair coexistence with incumbent technologies and work around Rel. 10/11 LTE without modifying the latter. First, Channel Selection senses the interference level in channel currently occupied by LTE. If high interference is detected the mechanism will switch LTE transmission to another cleaner channel. In cases when there are too many devices using the unlicensed band and a cleaner available channel cannot be found, LTE-U will share a channel with Wi-Fi STAs or other LTE-U devices using Carrier-Sensing Adaptive Transmission (CSAT) mechanism. CSAT senses the operating channel for a duration of up to 200 ms and analyses the interfering activity in the channel. Based on that information CSAT defines a duty cycle. LTE-U transmissions take place only during a fraction of the channel cycle time and the rest of the time transmissions are off giving up channel access to other RATs. Finally, it is suggested that LTE-U operates only in Supplemental Downlink (SDL) mode. In this mode, all the important control messages that require high QoS are transmitted and received by LTE stations only on the carrier with located in licensed bands, while the downlink data traffic can utilize both licensed and unlicensed bands. Downlink traffic on the SDL carrier is only turned on when the DL traffic in the licensed band exceeds an established limit, and turns off when load on the licensed carriers decreases. This procedure reduces the interference caused by LTE-U in the unlicensed bands.

LBT is a mechanism required in devices operating in unlicensed bands by the European Telecommunications Standards Institute (ETSI). It ensures that before transmitting on a channel a device must sense the interference level and only transmit when it cannot harm other devices' transmissions. In regions where LBT is required, such as Europe and Japan, modifications to the LTE standard have to be made by standardization organizations like 3GPP. Amendments and modifications to the LBT mechanism are addressed and documented in periodic releases of LTE standard, such as the upcoming 3GPP Release 14. As such, 3GPP initiated LTE-LAA in its latest releases in order to incorporate LBT into LTE and be able to use both licensed and unlicensed spectrums without harming performance of other RATs. Because more changes in the LTE standard are required to implement LTE-LAA than LTE-U, it is expected that LTE-U will be available for markets earlier. However, since LBT is planned to be adopted only by LTE-LAA, the latter will become a more popular and universal choice for both markets thanks to its robustness. Due to this reason, the emphasis of this work will be on LTE-LAA. The following sections will review the enablers of LTE-LAA, previous research in this topic including Wi-Fi/LTE-LAA coexistence analysis and variations in LBT design.

2.2 LAA Enablers

A. Listen-Before-Talk

One of the main enablers of LTE-LAA is the integration of LBT, a fair spectrum sharing mechanism, into the existing LTE standard. Basic principles of two types of the LBT mechanism are established by ETSI in [9]. The first type is Frame Based Equipment (FBE) LBT. In FBE, medium sensing followed by signal transmissions can occur only at specified periodic instances of time, similar to how LTE works. The second type is Load Based Equipment (LBE) LBT. Here, channel contention can occur at any time depending on the demand. Both forms of LBT are designed in order to enable fair medium sharing through carrier sensing, however, LBE provides more flexibility, while FBE offers easier temporal synchronization with LTE MAC layer.

LBE LBT requires that all RF devices operating in the 5 GHZ unlicensed spectrum perform a Clear Channel Assessment (CCA) check on the operating channel before any transmission. CCA observes the RF energy level for no less than 20 microseconds. The operating channel is said to be occupied if the observed energy exceeds a threshold (TL) given by

$$TL = -73 + (23 - Pt)\ [dBm / MHz] \qquad (1)$$

where Pt is the transmit power usually less than or equal to 23 dBm assuming a non-amplifying receive antenna. If the energy threshold is not exceeded, devices are allowed to transmit immediately. When the channel is busy, the initial CCA is followed by extended CCA (eCCA) usually referred to as the backoff period.

There are two options of LBE LBT that mainly differ in the contention window (CW) size selection. During eCCA in option A, the operating channel is observed for a period of q observation slots. An observation slot can be an idle eCCA slot of 18 microseconds or a busy slot which lasts from the end of the previous idle eCCA slot to the beginning of the next. Each time eCCA is being performed the channel needs to be idle for N unoccupied eCCA slots to begin transmission, where N is chosen randomly from 1 to q. If the channel is not idle for at least N eCCA slots out of q observation slots, the value of q is doubled and the procedure is repeated. The initial value of q is set to 16 and may reach 1024, after which it is reset back to the initial value. In option B, the value of q is chosen by the device manufacturer in the range 4 to 32. Here, the channel is observed for an observation period of N CCA slots ($N \times 20$ microsecond), where

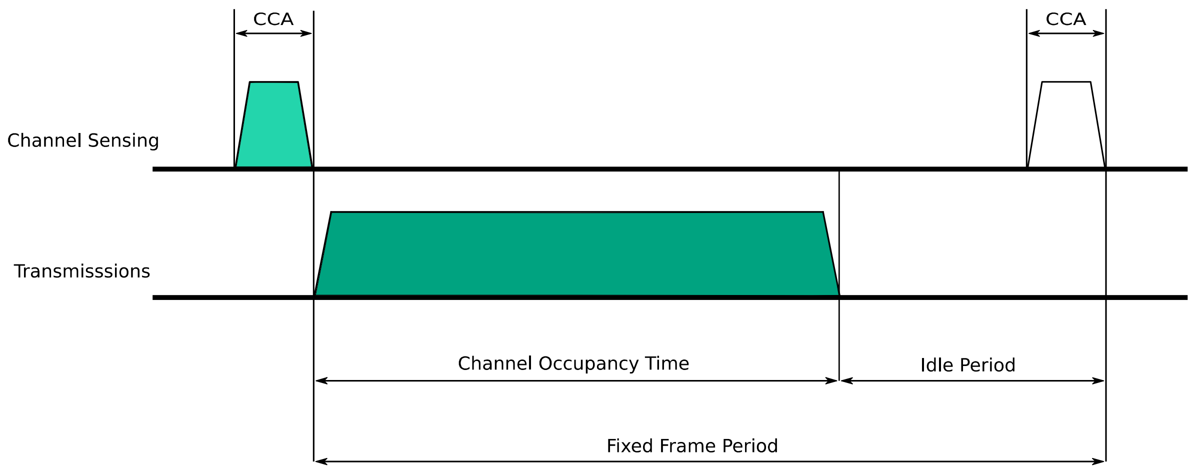

Figure 2. Structure of an FBE frame.

N is chosen randomly from 1 to q for each eCCA occasion. In both options, the total time that devices are allowed to transmit is the Maximum Channel Occupancy Time (MCOT) which may not exceed 10 milliseconds in option A or $(13/32)\times q$ milliseconds in option B. After this period, a device must perform a new eCCA check.

In FBE LBT, an analogous minimum 20 microseconds long CCA procedure is required before the start of a new frame. If the channel is found to be clear the device is allowed to transmit immediately, and in case of an occupied channel, all transmissions are disrupted for the entire duration of a Fixed Frame Period. A Fixed Frame Period is comprised of Channel Occupation Time (COT) and an Idle Period (Fig. 2). Transmissions are allowed only in COT and are not allowed during the Idle period. The maximum time an LBE device can occupy a channel between two consecutive CCAs must vary from 1 to 10 milliseconds. The allowed power levels are identical in both types of devices. In addition, devices are allowed to send ACK or Block ACK signals immediately after successfully receiving packets without performing CCA checks.

B. Carrier Aggregation

In Rel. 10 of the 3GPP LTE standard, also known as LTE-Advanced, the major modification was the introduction of Carrier Aggregation (CA), which brought several benefits to both LTE users and mobile operators [13]. CA is a technique that allows to increase the channel bandwidth by aggregating, or virtually concatenating up to five component carriers (CC). Each CC is comprised of multiple subcarriers, each 15 kHz apart, and can have a bandwidth of up to 20 MHz. Hence, using CA can produce a channel with a total 100 MHz bandwidth allowing for much higher data rates. In addition, intraband and interband configurations of CA are possible, where CCs may be contiguous or non-contiguous and belong to different bands (e.g. 800 MHz and 1800 MHz). This provides operators with increased flexibility to use their physical radio resources more efficiently by combining separate segments of available spectrum [2]. The use of unlicensed bands for LTE networks has been envisioned as an extension of this technique. It is suggested in multiple studies of LTE-LAA deployment scenarios that the SDL mode mentioned in Section 2-C is implemented using the CA technique. Specifically, in SDL LAA, the primary cell (PCell) operating in a licensed band with higher QoS is aggregated with secondary cells (SCell) in the available 5 GHz bands [14].

C. Discontinuous Transmission

In legacy LTE releases, a technique called Discontinuous Transmission (DTX) was introduced with a purpose of reducing power consumption on the UE end. This was achieved by scheduling subframes, during which the UE transmitter power amplifiers were switched off [15], [16]. The number and location of these subframes within a frame were determined based on the data carried in a certain subframe. This technique was also complemented by algorithms that optimized power consumption savings given additional constraints [17]. It was later proposed that these muted subframes can be used in order to prevent interference between LTE and Wi-Fi in the unlicensed bands. During powered off LTE subframes, Wi-Fi APs have access to the channel. During the rest of the LTE frame, LTE UEs utilize the same channel, thus taking turns operating in a certain unlicensed band without interference. A scheduling mechanism that would adjust the number of muted subframes as well their position within a frame is required to optimize the coexistence between different RATs. In [18], a similar technique known as Almost Blank Subframes (ABS), which mitigates interference between cells in HetNets by aggressively decreasing transmitted power during selected LTE subframes, is also proposed to be used in order to enable LTE – Wi-Fi coexistence.

D. Transmit Power Control

As was mentioned in Section 2.B, Transmit Power Control is a technique that adaptively reduces aggregate radiated power of LTE UEs by at least 3dB in order to bring co-channel interference down. TPC is proposed to be used to improve LTE - Wi-Fi coexistence [19], [20]. Measurements of external interference are performed repeatedly at UEs and are used to determine channel conditions in terms of neighboring Wi-Fi STAs. This information is then used to activate TPC and reduce radiated power if the detected interference reaches a certain threshold. This creates opportunities for Wi-Fi STAs to access the channel and optimizes the fairness of channel sharing between the two RATs.

2.3 Prior Research outcomes

The fundamental LBT rules specified in [9] were used by 3GPP to develop four major channel access scheme categories in [21]. These categories include: 1) no LBT, 2) LBT without random backoff, 3) LBT with random backoff and fixed CW size, and 4) LBT with random backoff and variable CW size. This section overviews categories 2 (based on ETSI FBE LBT), 3 and 4 (both based on ETSI LBE LBT) due to their fair coexistence nature. We focus on the most relevant previous works related to LTE-LAA that, in the author's opinion, will contribute to the eventual standardization of LTE-LAA in future 3GPP LTE releases.

In order to understand the factors that could cause potential degradation in Wi-Fi performance due to LTE-LAA, an experiment based study was conducted in [22]. The authors set up a physical Wi-Fi platform with 20 MHz bandwidth centered at 5.18 GHz and an LTE-A testbed with highly variable parameters that include bandwidth, center frequency and modulation schemes. In their experiments, two RAT testbeds were placed in a single room and operated in full buffer mode. LTE parameters were modified and the corresponding effect on Wi-Fi performance was observed. The results of the study showed that Wi-Fi transmissions were completely blocked by LTE transmissions with 3, 5 and 10 MHz bandwidths, unlike 1.4, 15, and 20 MHz, which only slightly affected the Wi-Fi performance. In addition, it was discovered that LTE with 1.4, 3 and 5 MHz bandwidths causes the Wi-Fi carrier sensing mechanism to falsely detect Wi-Fi preambles, thus halting all Wi-Fi transmissions. Hence, the study concluded that the wider LTE channel bandwidths were optimal for LTE-LAA adoption.

In [23], the authors propose a method of evaluating Wi-Fi - LAA coexistence. In their system model, 400 Wi-Fi STAs and 400 load based LAA UEs per km^2 were placed randomly on a virtual map based on a Poisson Point Process (PPP). Using this stochastic framework, authors provide mathematical models to be used as metrics for the evaluation. These include Medium Access Probability (MAP), Signal-to-Interference-plus-Noise Ratio (SINR) coverage probability, and Density of Successful Transmissions (DST). MAP is referred to as a probability that a channel is accessible by an average Wi-Fi/LAA device on the map. SINR coverage probability shows how likely the SINR at the receiving device is to be higher than a certain threshold T given interference from other APs and eNBs. Based on these two metrics, the DST was derived, which shows how many successful transmissions per unit area occur given a certain SINR sensitivity. In this study, the channel access mechanism is based on category 3 LBT with fixed CW size. In addition, two scenarios of LAA channel access

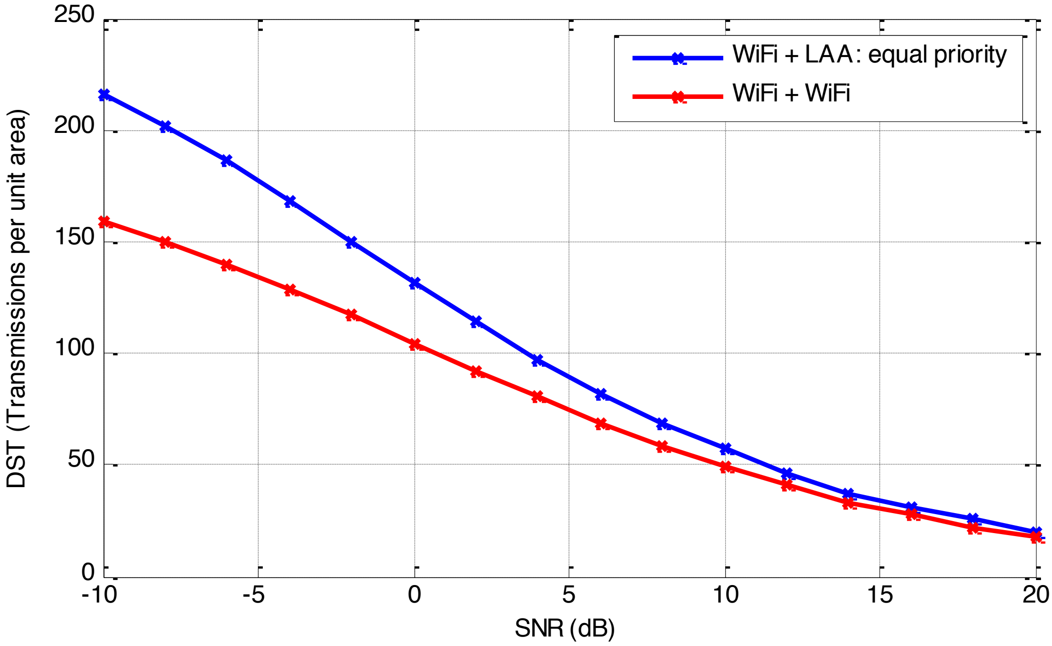

Figure 3.Density of Successful Transmissions when Wi-Fi coexists with LAA vs another Wi-Fi.

priority were considered. In the first scenario, LAA and Wi-Fi had equal channel access priority, while the second implemented LAA devices with a random backoff period longer than Wi-Fi's, thus having lower priority. The study concludes that LBT enabled LAA devices can be good neighbors to Wi-Fi STAs. Specifically, Fig. 3 shows better DST in a Wi-Fi STA coexisting with an LAA UE compared with a baseline scenario of two STAs sharing spectrum. This supports the idea that LAA devices can be a friendly neighbor to Wi-Fi STAs if an appropriate LBT mechanism is introduced.

The channel access mechanism considered in [24] is based entirely on LBE LBT with variable CW size as described in Section 3.A. In order to ensure fairness of channel sharing between LAA and Wi-Fi, the authors propose an important modification to the protocol. Specifically, it is suggested that after each

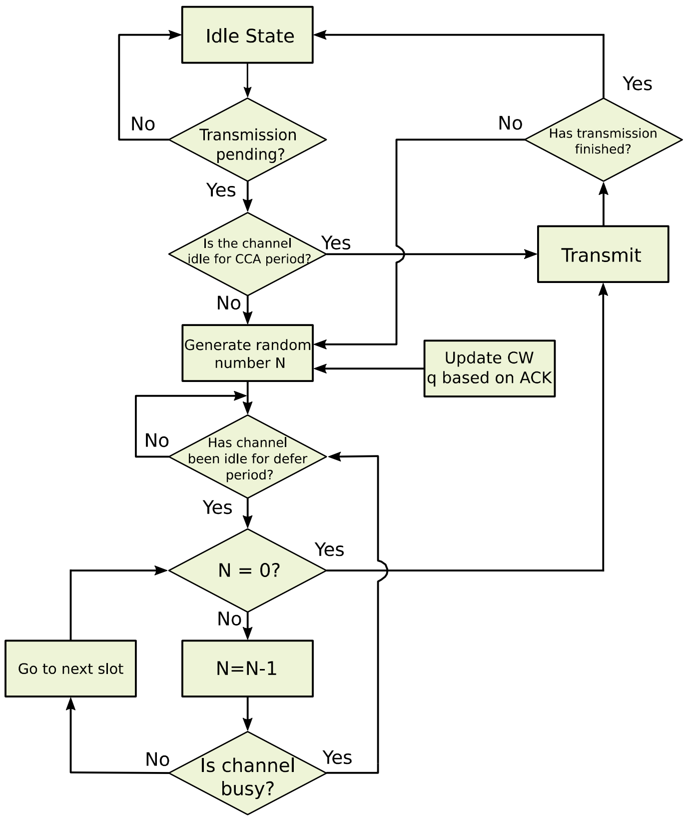

Figure 4. Block diagram of the LBT mechanism proposed in [16].

unsuccessful CCA or eCCA checks an additional defer period is introduced in LTE-LAA timing, similar in length to the 34 microsecond defer period already used in Wi-Fi DCF. Having this period would provide equal conditions for both RATs in accessing the channel since LTE-LAA would not have an advantage before Wi-Fi. The idea of adding an additional defer period to LBE LBT was also supported in [14]. Additionally, a new method of adjusting the CW size based on

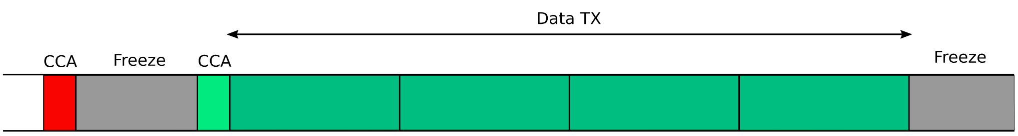

Figure 5. DTX frame with MCOT = 4 ms.

the current interference condition is proposed. If the receiver obtains a NACK signal, the CW size q is doubled. A diagram depicting the proposed LBT algorithm is shown in Fig. 4. The study concludes that implementation of an LBT mechanism with random backoff and defer periods can provide fair coexistence between LAA and Wi-Fi independent of the method of adjusting the size of window q.

In [25] an alternative LBT design based on Discontinuous Transmission (DTX) is considered. Here, the authors propose a modified LTE frame protocol where the maximum channel occupancy time is 4 ms, or 4 consecutive LTE subframe transmissions at a time followed by a freeze period. Each transmission burst is preceded by a CCA check and no transmissions are allowed until the next successful CCA check in order to provide fair spectrum sharing with other RATs and/or LAA devices (Fig. 5). In order to provide fair channel sharing and avoid blocking of Wi-Fi acknowledgement signals, an additional freeze period begins every time a channel becomes available. Since ACK signals do not require CCA checks in Wi-Fi DCF, this freeze period would ensure Wi-Fi STAs receive their ACK signals without interference from LAA UEs. Also, CCA instances are only allowed at subframe boundaries, which resembles the frame based LBT approach. The outcome of the simulations shows a considerable performance improvement in Wi-Fi throughput when a competing Wi-Fi STA is replaced by LAA UE.

An FBE based LBT approach is discussed in [26], [27]. The frame timing suggested here closely resembles the protocol developed by ETSI (Section 3.A) and is depicted in Fig. 2. In [26], an at least 20 microseconds long CCA procedure is performed before every frame, and if the channel is found to be busy, no transmissions occur for the following duration of a fixed frame time. Having this LBT frame structure is compliant with LTE frame timing, thus making it easier to implement LBT within the LTE protocol due to simpler synchronization. An adaptive CCA threshold algorithm proposed by the authors senses the energy levels of interfering signals before a CCA or eCCA checks. Based on the gathered statistics, a decision is made on whether to lower, keep, or raise the CCA threshold within an initial allowed range. The study concludes that CCA threshold can play an important role in the performance optimization of coexisting LAA and Wi-Fi systems. The proposed adaptive algorithm showed an increase in LAA capacity while keeping Wi-Fi performance unharmed. This was achieved when the CCA threshold was dynamically raised increasing frequency reuse in LAA UEs.

3. Description of conducted work & research

In order to investigate the effect that LTE-LAA with LBT has on the Wi-Fi performance, software simulation is used. The software chosen for this purpose is the LTE-A Link Level Simulator from the Vienna Simulator suite [28], which runs in MATLAB environment. To integrate LBT and CA into the LTE standard, modifications to the simulator were made, which required deep understanding of the simulator software structure. Additions and changes to the simulator are described in this chapter with the added code provided in Appendix A. After the necessary modifications were introduced, a series of simulations was performed with results presented and discussed in Chapter IV.

3.1 System model

The system model includes a single LTE-LAA UE that operates in 2.1 GHz licensed and 5.8 GHz unlicensed band. Carrier Aggregation is used to combine two 20 MHZ CCs from licensed and unlicensed bands. Both carriers operate in downlink only mode. The unlicensed band is shared with a single Wi-Fi AP that may transmit to devices with different data rates. Wi-Fi packet arrivals are modeled as a random Poisson process with average arrival rate λ. Scenarios with different values of λ corresponding to higher and lower channel loads are considered. Upon the reception of a Wi-Fi packet request, a file of size 0.5 MB is scheduled for transmission. Since the duration of a Wi-Fi slot is 9 microseconds, a packet arrival may occur in any of 111 Wi-Fi slots that can fit within a single LTE subframe. The duration of Wi-Fi packet transmissions is estimated according to

$$TxDuration = (\alpha \times F + \beta) \times 10^{-6} s \qquad (2)$$

where F is the size of a transmitted file, α and β are parameters that depend on the data rate of a current Wi-Fi transmission [29]. The current Wi-Fi data rate is chosen randomly and may take values: 6, 9, 12, 18, 24, 36, 48, and 54 Mbps all having equal probability of selection.

3.2 Proposed LBT technique

In this work, an alternative Category 2 LBT technique is proposed and studied. The frame structure of this design follows ETSI recommendations for FBE devices [9]. Here, a CCA check is performed before the beginning of every frame. If the channel is found to be busy, no transmissions happen for a duration of FFP. FFP is chosen so that it aligns with a 10 ms LTE frame. The choice of Category 2 LBT is made due to its simpler synchronization with LTE frame protocol within the chosen LTE simulator. In the proposed LBT mechanism, LTE transmissions may occur only during COT periods. The duration of COT can be adjusted based on the current channel conditions, similar to the MCOT limitation in [25], where it was done due to MCOT regulations set in certain locations. Here it is assumed that prior knowledge of the channel load statistics is available. This

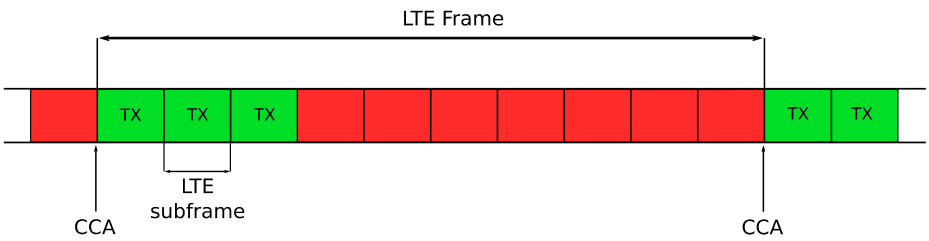

Figure 6. LTE frame with the proposed LBT mechanism.

statistic can be obtained by monitoring the Wi-Fi preamble signals on the LTE-LAA eNB. Scenarios with different channel loads (i.e λ values) are considered. Additionally, if an LTE transmission is paused due to a new Wi-Fi transmission outside of the COT period, it will resume transmitting only during future COT periods after Wi-Fi finishes its own transmission. An LTE frame with the proposed LBT mechanism is shown in Fig. 6. The COT in this example is 3 milliseconds, which corresponds to 3 LTE subframes.

4. Presentation of Results

A series of simulation runs was performed to obtain the numerical estimation of the impact that LTE-LAA has on Wi-Fi performance. The results of simulations with varying parameters like packet arrival rate λ and COT values are graphically presented in this chapter.

Details on the parameters for all simulation runs are indicated in Table 1.

Table 1. Simulation Parameters for Wi-Fi and LTE models.

Parameter	Value
Number of transmitted LTE subframes	1000
SNR	[-9:21]
CQI index	1
Unlicensed carrier BW	20 MHz
Unlicensed carrier center frequency	5.8 GHz
Licensed carrier BW	20 MHz
Licensed carrier center frequency	2.1 GHz
Channel estimation model	Perfect
LTE MIMO configuration	2×2
Wi-Fi packet arrival rate, λ	1, 2
Channel Occupation Time duration	1, 3, 5 ms
Wi-Fi TX data rate	6, 9, 12, 18, 24, 36, 48, 54 Mbps
Wi-Fi TX file size	0.5 MB

Fig. 7 shows the LTE-LAA throughput in the unlicensed band only for the case when λ = 1. This corresponds to the scenario with a lower channel load of one Wi-Fi transmission request per second. Results corresponding to the case where $\lambda = 2$ are shown in Fig. 8.

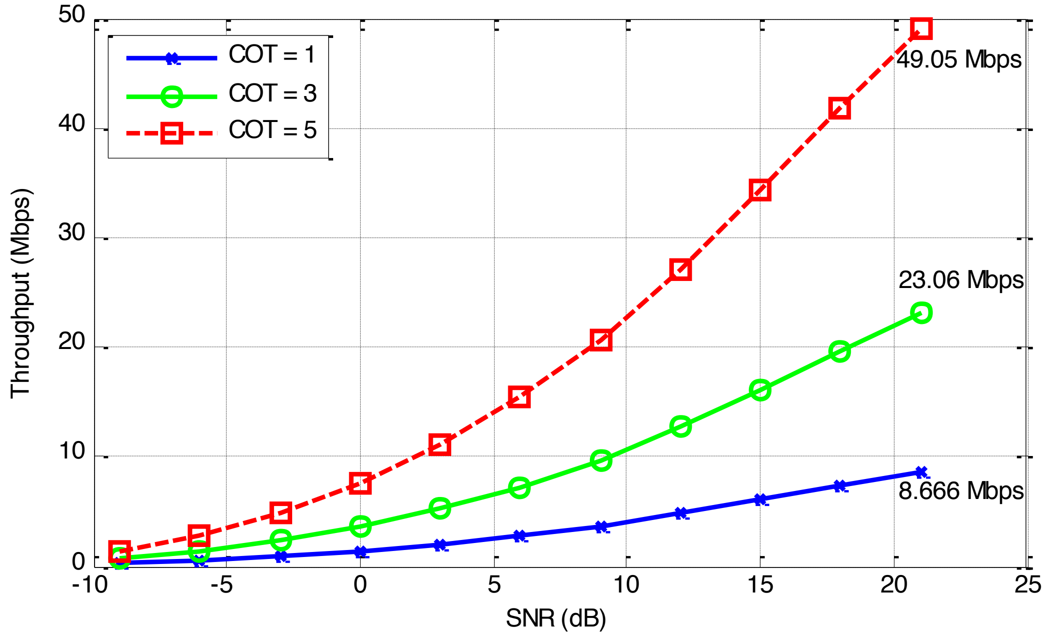

Figure 7. LTE-LAA throughput in the unlicensed bands, λ = 1.

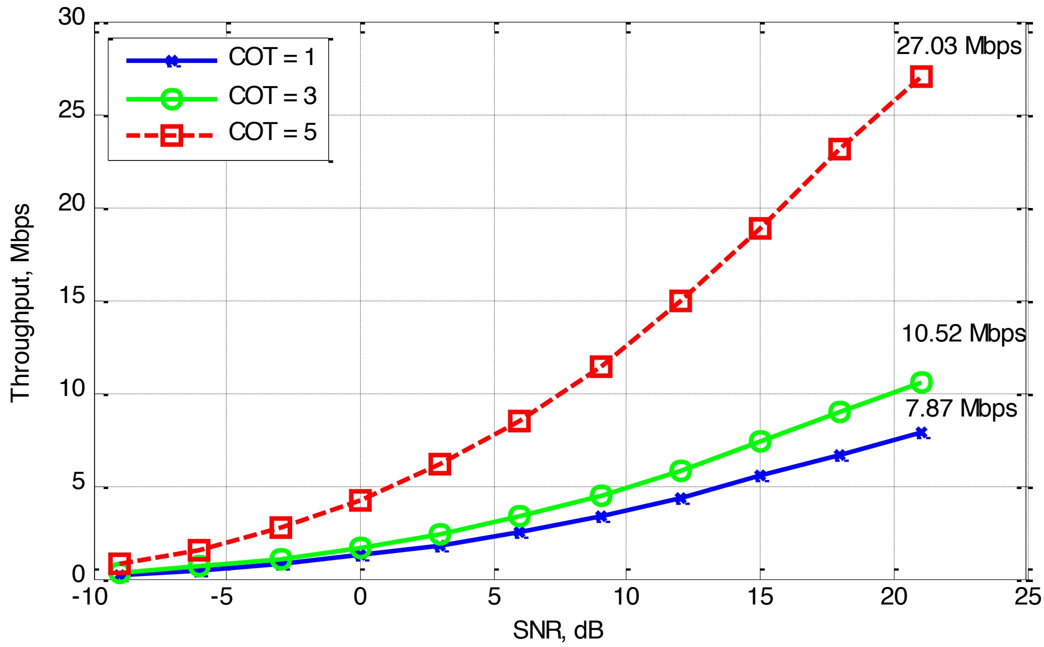

Figure 8. LTE-LAA throughput in the unlicensed bands, λ = 2.

Figs. 9 and 10 show the LTE-LAA aggregated throughput including both licensed and unlicensed carrier components for the cases with lower and higher channel loads respectively.

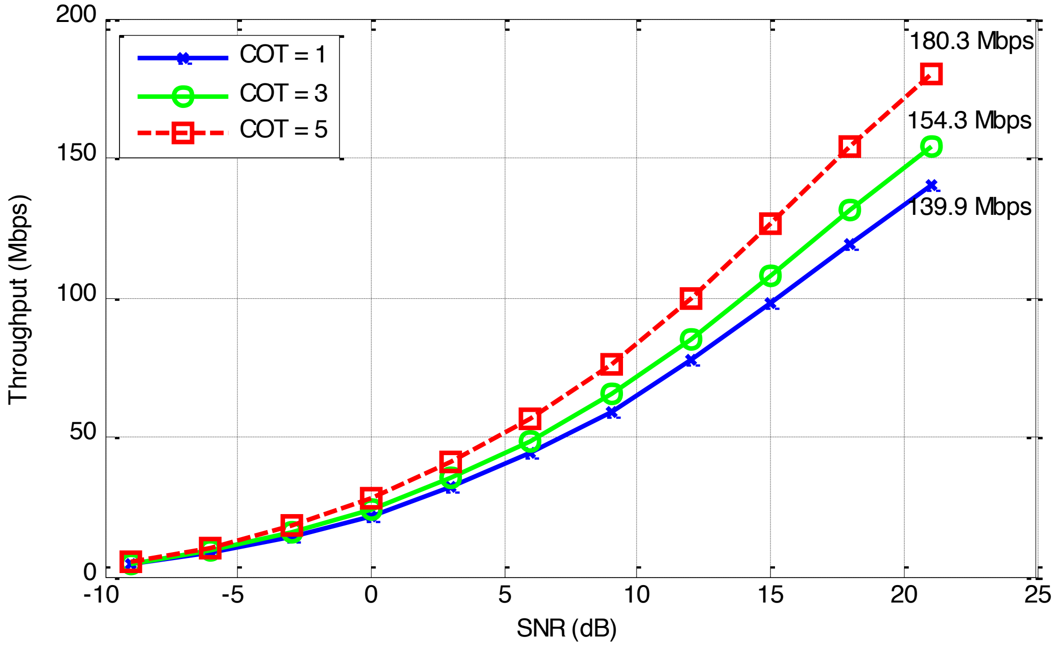

Figure 9. LTE-LAA throughput in the unlicensed and licensed bands, λ = 1.

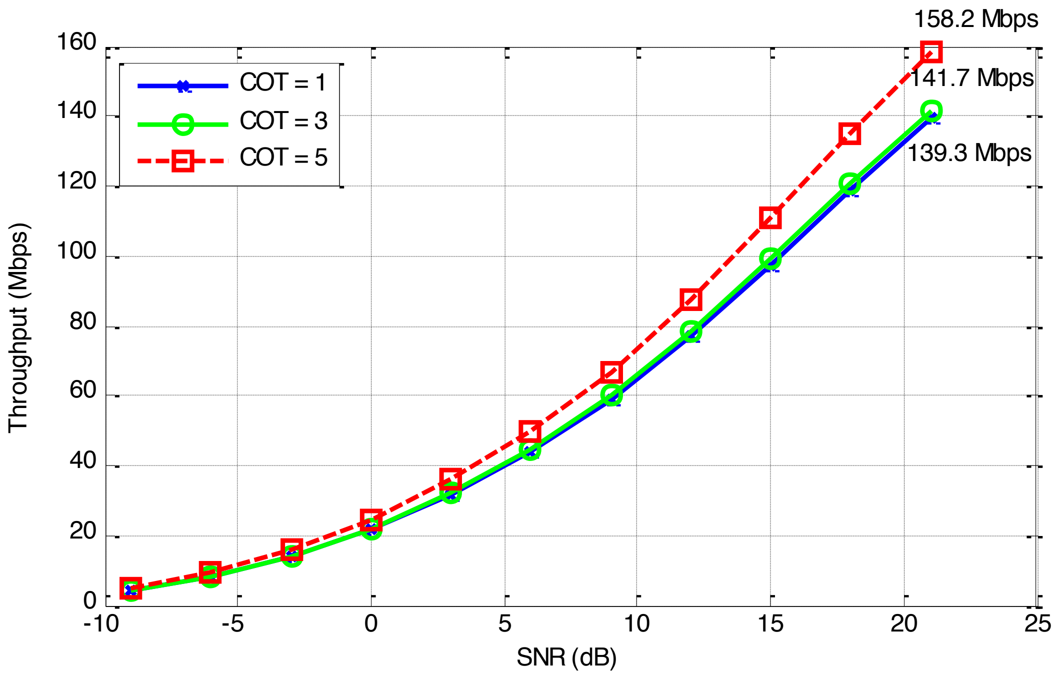

Figure 10. LTE-LAA throughput in the unlicensed and licensed bands, λ = 2.

For comparison, Fig. 11 shows throughput for the case when LTE operates without LAA in a single licensed band centered at 2.1 GHz.

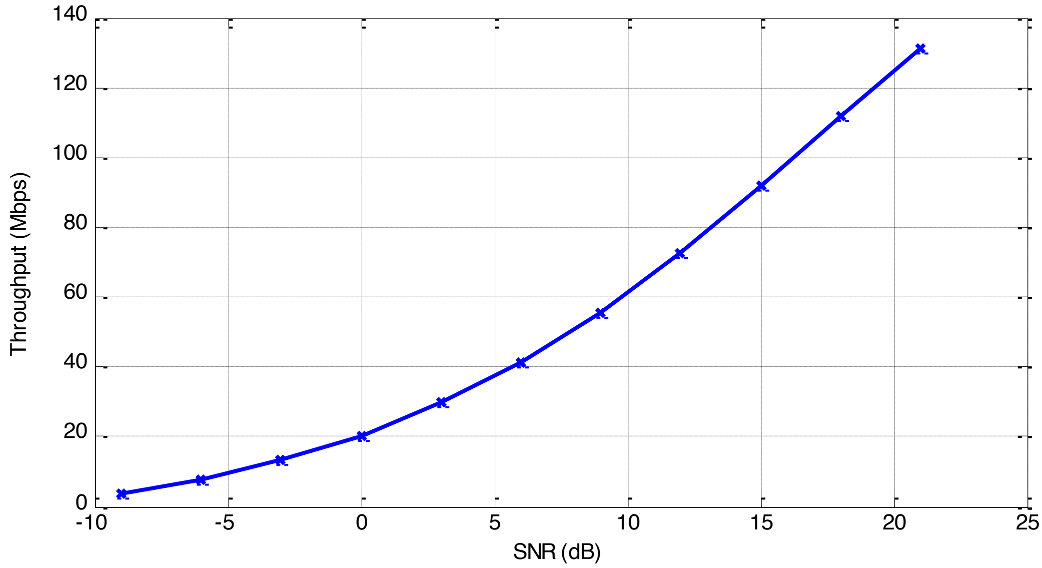

Figure 11. LTE throughput in 2.1 GHz licensed band.

As can be seen in Figs. 7 and 8, LTE-LAA throughput in the unlicensed band is directly proportional to the COT value. This was expected since longer COT duration results in more transmission opportunities available to LTE-LAA eNBs. In addition, we can observe higher LTE-LAA throughput gains for the scenario with the lower channel load.

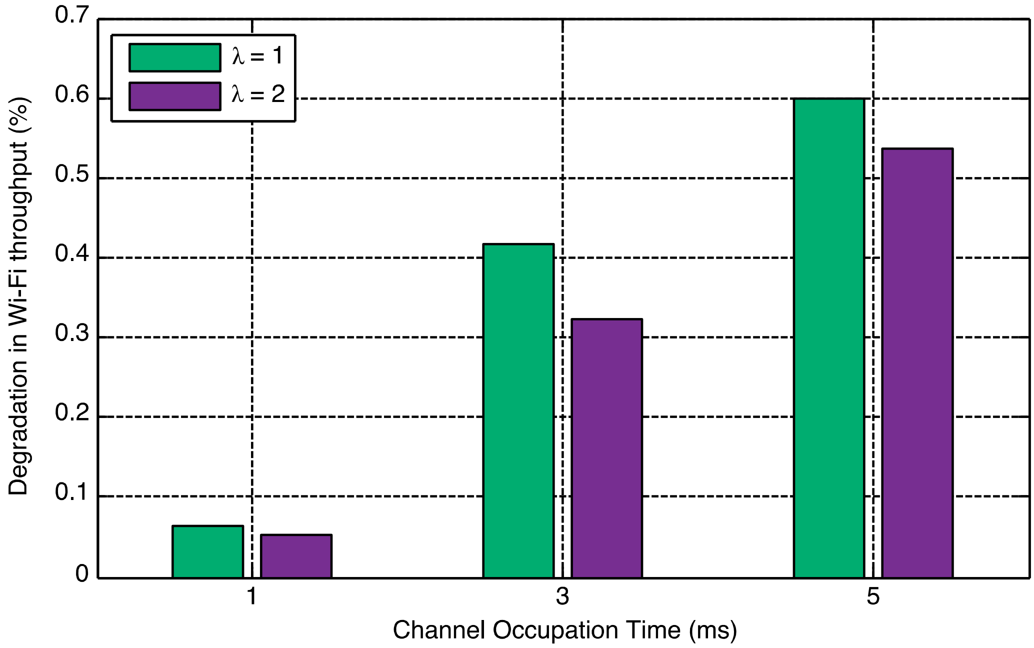

Figure 12. Average Wi-Fi throughput degradation due to LTE-LAA.

Finally, the Wi-Fi throughputs for the cases when Wi-Fi shares the channel with LTE-LAA and when the Wi-Fi AP operates with no external interference are compared. The latter value is obtained by estimating the total transmission time of the randomly generated number of Wi-Fi packets. Table 2 shows the number of files transmitted over Wi-Fi in each simulation run, depending on the values of λ and COT. Fig. 12 shows the average Wi-Fi throughput degradation percentage due to LTE-LAA for the low and high channel load cases as the COT value increases. Again, an expected trend can be observed, as the degradation in Wi-Fi performance increases with longer COT values, with the highest throughput loss of 0.6%. The result also suggests that Wi-Fi APs with higher channel loads suffer less degradation due to LTE-LAA.

Table 2. Number of files transmitted over Wi-Fi for different LTE-LAA configurations.

COT / λ	1 ms	3 ms	5 ms
1	16	10	3
2	28	32	8

5. Conclusions

The potential benefits that LTE-LAA could bring to wireless service providers have attracted a lot of attention in recent years. The ability to significantly increase network throughput by gaining additional physical radio resources in the unlicensed spectrum has been the goal of many researchers and institutions that have planned to standardize this technology in the nearest LTE releases.

In this work, various techniques previously used for implementation of LTE in unlicensed bands are used to test an alternative LBT channel contention mechanism, which is required in LTE-LAA in order to coexist with other RATs operating in the same bands. The simulation results showed that an FBE LBT approach with varying COT values can provide increased LTE throughput without significant Wi-Fi performance degradation. A direct dependency between COT values and degradation has been observed. Also, it was discovered that Wi-Fi APs operating in less congested channels suffer higher performance degradation than APs operating in channels with a higher load. A maximum degradation of 0.6% has been observed for the case when $COT = 5ms$ and channel load parameter $\lambda = 1$.

The presented system model considers a single LTE-LAA EU for simplicity. In a realistic scenario where many UEs are densely congesting a certain area, individual LTE-LAA UEs would gain less additional throughput, while the performance boost of an overall LTE network would remain as in the case with a single UE. In addition, due to the frame based nature of the proposed LBT technique, the degradation in Wi-Fi performance is expected to remain the same.

Future Work

As an extension to the current thesis, a category 4 LBE LBT mechanism can be integrated into the simulator and evaluated. This type of LBT mechanisms has gained vast popularity among regulatory bodies and requires more attention from researchers. Additionally, the implementation of Wi-Fi activities in the used simulator can be reconsidered. Introducing MCOT periods in Wi-Fi transmissions would make the system model more realistic. This is expected to raise the LTE-LAA throughput, but also increase the Wi-Fi performance degradation.

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Appendices

Appendix A

The following code was added to the file *LTE_sim_main_process_SNR_point.m* within the Vienna LTE-A Link Level simulator package. Provided code is a part of the newly created parallel processing chain corresponding to the carrier in the unlicensed band.

This part loads the predefined configuration for the Single User MIMO enabled scenario:

```
LTE_params =
simulation_config.LTEA_SUMIMOconfig.apply_parameters(LTE_param
s);
```

This part sets the unlicensed carrier bandwidth to 20 MHz and the operating frequency to 5.8 GHz

```
LTE_params.Bandwidth = 20e6; % Channel Bandwidth in Hz
LTE_params.carrier_freq = 5.8e9; % Carrier frequency in Hz
```

This part chooses the coarsest PMI and CQI granularity (number of occupied resource blocks) based on the BW defined earlier. This is required for the simulator core.

```
switch LTE_params.Bandwidth
    case 1.4*10^6
        LTE_params.UE_config.PMI_fb_granularity = 6;
        LTE_params.UE_config.CQI_fb_granularity = 6;
    case 3*10^6
        LTE_params.UE_config.PMI_fb_granularity = 15;
        LTE_params.UE_config.CQI_fb_granularity = 15;
    case 5*10^6
        LTE_params.UE_config.PMI_fb_granularity = 25;
        LTE_params.UE_config.CQI_fb_granularity = 25;
    case 10*10^6
        LTE_params.UE_config.PMI_fb_granularity = 50;
```

```
        LTE_params.UE_config.CQI_fb_granularity = 50;
    case 15*10^6
        LTE_params.UE_config.PMI_fb_granularity = 75;
        LTE_params.UE_config.CQI_fb_granularity = 75;
    case 20*10^6
        LTE_params.UE_config.PMI_fb_granularity = 100;
        LTE_params.UE_config.CQI_fb_granularity = 100;
end
```

This part re-generates parameters required for the simulator based on the new values of BW, carrier frequency, and feedback signals granularity. This is done by calling external functions `LTE_load_parameters_dependent` and `LTE_load_parameters_generate_elements`.

```
[LTE_params,ChanMod,winner_channel,winner_out] =
LTE_load_parameters_dependent(LTE_params,N_subframes,SNR_vec);
[LTE_params,eNodeBs,UEs,ChanMod,BS_coordinator,Interferers,SNR
_vec,SIR_vec] =
LTE_load_parameters_generate_elements(LTE_params,ChanMod,cqi_i
,SNR_vec,SIR_vec);
```

This part initializes data rates, code rates, parameter λ, file size, time resolution for Poisson distribution, α and β parameters for the Wi-Fi transmissions:

```
DR = [6    9    12    18    24    36    48    54]; % Nominal data
rates
CR = [0.5 0.75 0.5 0.75 0.5 0.75 0.67 0.75]; % Code rates
corresponding to data rates
lambda = 2; % Average number of Wi-Fi packet arrivals
deltaT = 1e-3; % Poisson distribution time resolution
alpha_param = [1.3333 0.8889 0.6667 0.4444 0.3333 0.2222
0.1667 0.1481]; % Parameters used to estimate transmission
time of a data file as described in Section 3.1
beta_param = [169.8333 167.0556 165.6667 164.2778 163.5833
162.8889 162.5417 162.4259];
file_size = 0.5e6; % File size in bytes
```

This part initializes variables required to keep track of COT subframes and variables that handle Wi-Fi transmissions.

```
wifi_tx_pend = 0; % Initially there are no pending Wi-Fi
transmissions
wifi_tx_current = 0; % No transmissions happening currently
```

```
laa_COT = 5; % Fixed number of COT subframes
wifi_packets = 0; % Initial number of transmitted Wi-Fi
packets
save_idx = 0; % This dummy index will be used to save Wi-Fi
transmission records
Duration_total = 0;  % Initial duration of Wi-Fi transmissions
wifi_waiting_cntr = 0; % Initial time Wi-Fi spends in awaiting
wifi_tx_time = 0; % Time that Wi-Fi has been transmitting
until current network time
```

This part loads the previously saved random stream and resets it to be able to generate the same Poisson distribution for different SNR values:

```
load('./results/simulations/saved_vars/s.mat'); % load the
random stream
reset(s); % reset the random stream
```

The following line advances the network time by 1 millisecond and increments the number of Transmission Time Intervals (TTI). The final count of TTIs that it takes the simulator to transmit all necessary subframes in the unlicensed band is used later to evaluate the average LTE-LAA throughput for a range of different SNR values. This value can be retrieved from the object *network_clock* of class *network_elements.clock*.

```
network_clock.advance_1_TTI;
```

The variable *xy* indicates whether LTE – LAA can acquire the channel in this TTI, and cancels skipping of the frame if it is the beginning of a new frame.

```
xy = mod(network_clock.current_TTI, 10);
if xy == 1 % reset value of skip_frame
   skip_frame = 0;
end
```

This part performs CCA and updates Wi-Fi TX time, as well as the number of transmitted files:

```
if wifi_tx_current == 1 % Check if there is an ongoing
transmission
    skip_frame = 1; % LTE-LAA is set skip the remainder of
this frame
    wifi_tx_time = wifi_tx_time + 1e-3; % update time that Wi-
Fi has been transmitting
    if wifi_tx_time > Duration_total
        wifi_tx_current = 0; %reset value since Wi-Fi
transmission will have finished by end of current TTI
        wifi_packets = wifi_packets + 1; % number of finished
Wi-Fi file transmissions
    end
end
```

This section generates a Poisson random distribution within the previously loaded random stream *s*. Data rate and code rate for the new Wi-Fi TX are generated; variables handling Wi-Fi transmissions are updated.

```
if s.rand < lambda * deltaT % this approximates a Poisson
distribution for a large number of trials with an average
number of arrivals lambda.
    wifi_tx_pend = wifi_tx_pend + 1; % this will indicate the
number of pending TX requests that has accumulated in a First-
in-First-out stack until the current network time
    rq.DR_idx = s.randi(8); % choose 1 of 8 data rates
    rq.DR_used= DR(rq.DR_idx); % random data rate from the
selection of 4 nominal data rates in DR
    rq.CR_used = CR(rq.DR_idx); % code rate that corresponds
to the chosen datarate
    rq.TxSlot = s.randi(111); % choose one of the 111 Wi-Fi
slots within the current subframe where arrival happens
    save_idx = save_idx + 1;
    rq.TTI_idx = network_clock.current_TTI; % save TTI of the
request time
```

This part calculates the duration of the currently pending Wi-Fi TX and updates the waiting time until the Wi-Fi TX begins. Also, transmission request details are saved for future reference.

```
    rq.TxT0 = network_clock.time + rq.TxSlot * 9e-6; %TxT0 is
the network time where Wi-Fi packet arrival happens; 9e-6 is 9
microseconds Wi-Fi slot duration
    rq.TxDur = (alpha_param(rq.DR_idx) * file_size +
beta_param(rq.DR_idx)) * 1e-6; % duration of a file
```

```
transmission in seconds; this formula is referenced in Section
3.1.
    if xy > 0 && xy < (laa_COT+1) % Wi-Fi is not allowed to
transmit immediately
        wifi_waiting_cntr = wifi_waiting_cntr + (111 -
rq.TxSlot) * 9e-6; % add the remainder of this subframe to
total Wi-Fi waiting time
    end
       rq_new(wifi_tx_pend) = rq; % this vector will save the
last pending Wi-Fi request (some are removed as they get
transmitted)
       rq_all(save_idx) = rq; % this saves all request details
into vector rq_all
end
```

This part checks which part of a DTX frame it currently is. If it is LAA COT and there is a pending Wi-Fi transmissions, Wi-Fi waiting time is updated. If it is Wi-Fi COT and there is a pending transmission, start Wi-Fi TX immediately and stop LTE transmissions.

```
if xy > 0 && xy < (laa_COT + 1) % It is now LTE-LAA COT period
    if wifi_tx_pend > 0 && wifi_tx_current == 0
        wifi_waiting_cntr = wifi_waiting_cntr + 1e-3; % Update
Wi-Fi waiting time
     end
else % it is now Wi-Fi COT; stop all LTE transmissions
     if wifi_tx_pend > 0 && wifi_tx_current == 0 % Start Wi-Fi
TX
         rq_old = rq_new(1); % temporarily save details of the
new Wi-Fi request
         Duration_total = Duration_total + rq_old.TxDur; % Sum
of Wi-Fi TX durations up to the current request
         rq_new(1) = [];% Delete the newly initiated FIFO Wi-
Fi request from the vector;
         wifi_tx_current = 1; % Indicate that Wi-Fi is
currently transmitting
         wifi_tx_pend = wifi_tx_pend - 1; % Decrement number
of remaining Wi-Fi requests
         wifi_tx_time = wifi_tx_time + (111 - rq_old.TxSlot) *
9e-6; % Update time that Wi-Fi has been transmitting
      end
      skip_frame = 1; % Indicate that LTE must skip this frame
end
```

This part skips this simulator iteration without updating the subframe index if the *skip_frame* flag is set. Hence, the current subframe data will be attempted to transmit at a later instance.

```
if skip_frame == 1
    continue % skip this loop iteration
end
```