COMPARATIVE SURVEY OF STUDIES OF COEXISTING WI-FI AND LTE NETWORKS

by

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The recent global increase in mobile data traffic has service providers examining new ways to meet this traffic demand. While the licensed spectrum is the main way of providing data services, the available spectrum in the licensed band is limited and expensive. The unlicensed band, on the other hand, has a vast amount of available spectrum (> 400 MHz), together in the 2.4 and 5 GHz bands. Based on the link performance, medium access control, and advanced scheduling algorithms, LTE is an efficient way of leveraging the unlicensed spectrum by service providers. Depending on the regulation requirements, LTE in the unlicensed band can be deployed as LTE-U (unlicensed) or as LAA (licensed assisted access). However, deploying LTE in the unlicensed band interferes with the existing technologies that use the same frequency band like Wi-Fi. It is unclear to what extent this interference impacts both legacy technologies and LTE-U/LAA. This thesis surveys the research that has been done until now in this field and compares the evaluations of the performance of LTE and Wi-Fi and the issues that arise when they coexist.

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PREFACE

I would like to express gratitude to my thesis advisor, Dr. Prashant Krishnamurthy, Dr. Martin Weiss and to my program advisor Dr. David Tipper, for their help and offered invaluable assistance, support and guidance throughout this work and during my studies.

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1.0 INTRODUCTION

The high increase in mobile data consumption has raised the industry's concern on how to meet this traffic demand. The industry is getting ready for a 1000× increase in mobile data traffic, or what is known as the 1000× mobile data challenge [1]. While licensed spectrum is reliable and can help maintain quality of service to the customers, it is scarce and expensive. One of the best ways to address the challenge is by using (in the most efficient way) the unlicensed spectrum.

One of the disadvantages of the unlicensed spectrum is that it is shared between different technologies and users, which sets back the ability to provide high-quality services at all times. Unlicensed bands, on the other hand, have a vast amount of available spectrum (> 400 MHz), together in the 2.4 and 5 GHz bands. The frequency band of most interest for 3GPP (the standard's body for both 4G and 5G cellular) is the 5 GHz band, which has a lot of unlicensed spectrum available globally, much more than the 2.4 GHz band.

- In USA, the 5 GHz band has approximately 580 MHz of spectrum
- In Europe, it has around 455 MHz
- In China, it has around 325 MHz

While the transmission range is higher at 2.4 GHz, the 2.4 GHz band has fewer channel options (only 3 non-overlapping channels). The 5 GHz band has 23 non-overlapping channels in comparison.

Based on the link performance, medium access control, and advanced scheduling algorithms, LTE, the 4G standard, is an efficient way of leveraging unlicensed spectrum by service providers. Since LTE was designed for high-quality performance in dense deployments it was just a matter of time until it was introduced also for use in the unlicensed band. The advantages that LTE has over wireless local area network standards like Wi-Fi are: better link performance, scheduled medium access control, mobility management and excellent coverage. From the service providers point of view it thus makes more sense to deploy LTE in the unlicensed spectrum because of the increased bandwidth to serve more number of users, cheaper operating fee (as no license fee is charged for the use of unlicensed band), and LTE-Unlicensed is transparent to the LTE core network, which means a service provider does not need to upgrade the Evolved Packet Core (EPC) network elements. To exploit these advantages, the industry came up with LTE in the unlicensed spectrum in the form of: LTE-U (LTE-Unlicensed) and LAA (Licensed Assisted Access).

However, the deployment of LTE in the unlicensed band creates interference for the existing technologies that use the same frequency band, like Wi-Fi. The extent of this interference is unclear and depends on the nature of the protocol and factors such as distances between interferers and transmit power.

This thesis surveys the research that has been done until now in this field and compares the evaluations of the performance of LTE and Wi-Fi and the issues that arise when they coexist. The objective of this thesis is to extract the common inferences from these papers for a better understanding of the coexistence problem.

1.1 THESIS STRUCTURE

The structure of the thesis is given below:

Chapter II introduces a brief overview of LTE and Wi-Fi and the coexistence issues that arise when they are in the presence of each other. In Chapter III, the method used for comparing the performance of LTE and Wi-Fi networks while coexisting is presented, along with results from the surveying of papers. The selected papers are classified and the parameters leading to the classification are described. In Chapter IV the comparison of the papers is presented and discussed. Finally, in Chapter V the conclusions of this thesis are presented.

2.0 BACKGROUND

In this chapter, we will discuss briefly discuss, the technologies of LTE and Wi-Fi, and their different channel access mechanisms. We will discuss industry proposals for addressing the rising mobile data traffic with different approaches for dealing with the coexistence issues that arise. At the end of this chapter, related work on the coexistence of Wi-Fi and the different types of LTE in the unlicensed bands are presented.

2.1 WI-FI

Wi-Fi is a WLAN (Wireless Local Area Network) technology, which enables wireless devices like smart phones, laptops and tablets, and other devices like cameras and smart locks to connect to the internet via a Wi-Fi access point and communicate with another Wi-Fi device. The main reason why Wi-Fi is designed to function in the unlicensed spectrum is because technologies can operate in the unlicensed band free of charge, and people can deploy them without explicit permission from regulatory bodies, such as the US Federal Communications Commission.

The advantages of Wi-Fi networks, which are: easy set-up, low cost, high data rate, short round trip delay and low cost, make Wi-Fi the most popular Wireless LAN technology. Since in this work we study the coexistence issue between Wi-Fi and LTE in the unlicensed, the medium access control (MAC) layer mechanism of Wi-Fi is described next.

As we know the MAC layer is the protocol layer between the Physical and Network layers. The role of the MAC of Wi-Fi is controlling and maintaining the communication in Wi-Fi networks by coordinating the access of a shared channel between different Wi-Fi devices simultaneously.

The more popular MAC Wi-Fi mechanism is Distributed Coordination Function (DCF). DCF is based on CSMA/CA (Carrier Sense Multiple Access/ Collision Avoidance). Briefly, the Wi-Fi device first senses the channel before making a transmission, and performs a “Clear Channel Assessment (CCA)” mechanism. If the channel is detected as available or free for a period of time called - DIFS (Distributed Inter- Frame Space), the transmission continues. If during transmission a collision happens, the Wi-Fi device enters back-off and waits for a random time before trying again. With every collision that happens the random value is doubled. Collisions are *indirectly* detected when the receiving device fails to acknowledge a frame.

The other Wi-Fi MAC protocol is the centralized Point Coordination Function (PCF) mode that uses polling, but because DCF is more scalable and widespread in use, PCF is of lesser importance for this work.

2.2 LTE

LTE (Long Term Evolution of UMTS) is a mobile communication standard purposed for the communication of wireless devices and data terminals in a variety of licensed bands (e.g., 700 MHz in the US). It is continuously called 4G in the media. LTE, also called E-UTRAN (Evolved Universal Terrestrial Access Network), which was introduced in 3GPP Release 8, is the access part of what is called the Evolved Packet System (EPS). The requirements for LTE are high spectral efficiency, high peak data rates, short round trip time as well as flexibility in frequency and bandwidth [2].

LTE is purely IP based, so that IP address allocation is done when the mobile device is switched on and then released when switched off. This is similar to Wi-Fi which also gets an IP address when a device is switched on, using the dynamic host configuration protocol (DHCP) in local area networks. The access method LTE uses is based on OFDMA (Orthogonal Frequency Division Multiple Access) with a combination of higher orders of modulation with large bandwidths and spatial multiplexing in the downlink. Theoretically, the highest peak data rate that can be achieved in LTE Rel. 8, with 64-quadrature amplitude modulation (QAM) on the transport channel in the uplink is 75 Mbps, while in the downlink can support up to 300 Mbps.

LTE is synchronous and by nature is centralized. The LTE radio frame duration is 10ms (See Figure 1). Then each frame is divided into 10 sub-frames of 1ms duration each. These sub-frames are divided into 2 slots of 0.5ms, which contain a set of time symbols which are called OFDM symbols. OFDMA (orthogonal frequency division multiple access) enables simultaneous transmissions for multiple users in LTE. Within a cell, all LTE transmissions are assigned to the slots by a LTE base-station scheduler. Since in LTE the scheduling is carried out in a centralized manner, the user devices that are in the same cell must be tightly synchronized.

Unlike Wi-Fi, LTE devices do not perform carrier sensing before transmission. This is a primary reason why coexistence issues arise and why different types of coexistence mechanisms had to be developed for LTE to avoid the interference with Wi-Fi as we discuss in the section 2.2.1

LTE Release 8 was the first launched LTE technology, and contrary to the marketing hype it did not meet the technical criteria of 4G wireless service. After release 10 of LTE, more advanced technologies were implemented and the new name for LTE since then became LTE-A (LTE Advanced). Release 10 of LTE was the first standard to fulfill the 4G requirements and ITU defined LTE-A as “True 4G”.

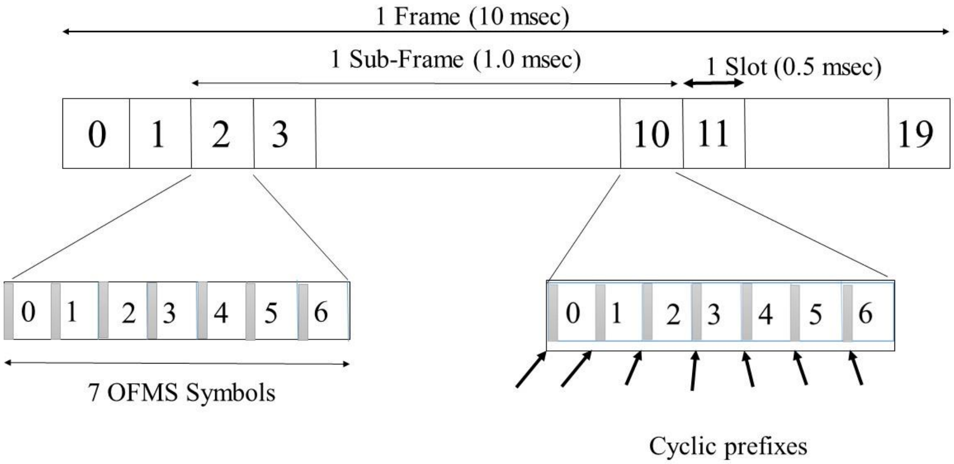

Figure 1. LTE frame format

The reason why LTE-A is important for this thesis, is that it is the first release to include data offloading from LTE to the unlicensed spectrum.

The goal of LTE-A is delivering extremely reliable and high-level performance services to the customers, and that is why it functions in the licensed band. The interference from unlicensed users is non-existent since only LTE-A licensed users can transmit the in licensed frequency bands and they are separated in space, time, or frequency.

Introducing LTE in the unlicensed band enables service providers to improve their existing services and keep up with the growing demand. So, the industry came up with four main types for deploying LTE in the unlicensed spectrum, those being:

- LTE in the unlicensed Spectrum (LTE-U)
- Licensed Assisted Access (LAA)
- LTE- Wi-Fi Aggregation (LWA)
- MulteFire

2.2.1 LTE- U

LTE- Unlicensed or LTE-U is developed by the LTE-U forum. It is the first offloading technology to be introduced in Release 10 feature Carrier Aggregation. LTE-U is based on Release 10, 11 & 12 and implements only Supplemental Downlink or SDL (Carrier Aggregation in Uplink not needed). Supplemental Downlink means using the unlicensed band with downlink carrier aggregation only. This way the downlink capacity is enhanced by utilizing *additional carriers* in the unlicensed spectrum, along with the primary carriers in the licensed spectrum.

Since LTE-U does not implement the Listen Before Talk (LBT) protocol that is required in many countries, it is to be deployed in non LBT markets, namely USA, China, Korea, India. The LBT protocol will be explained in section 2.2.2. LTE-U establishes coexistence through these three mechanisms:

- Channel selection
- CSAT (Carrier Sense Adaptive Transmission).
- Opportunistic Secondary Cell Switch-OFF

We explain each briefly below.

Channel Selection – This enables the small cells (based on the LTE and the Wi-Fi measurements that are done) to select the "cleanest" channel band. The channel which has the least usage is referred as the cleanest channel. This way the interference is avoided between say Wi-Fi and LTE-U. If the need arises it will change the channel and select a more suitable one.

CSAT (Carrier Sense Adaptive Transmission) – is used in the case when there is no clean channel available. Based on the 10s -100s of carrier sensing of co-channel Wi-Fi activities, CSAT algorithm applies adaptive or static Time Division Multiplexing (TDM) transmission to LTE-U small cells. This guarantees that LTE-U nodes can share the channel fairly with the neighboring Wi-Fi access points even in dense deployments.

Opportunistic Supplemental Downlink– One assumption for the use of unlicensed spectrum is that it can be used when licensed spectrum is fully utilized. Opportunistic SDL assumes that licensed spectrum is always available and unlicensed spectrum can be used opportunistically as needed. When the downlink traffic exceeds a defined threshold, and users are within the unlicensed spectrum area, the secondary carrier in unlicensed spectrum can be turned on to support the primary carrier in licensed spectrum for offloading. When the traffic can be managed by the primary carrier, the secondary carrier can be turned off.

2.2.2 LAA

Licensed Assisted Access (LAA) is a global solution that promises fairness between the spectrum use of LTE and Wi-Fi.

3GPP initiated a “Study item” for LAA which was followed by LTE Release 13 Work Item. The “Study item” [3] identifies multiple deployment scenarios for LTE in the unlicensed spectrum focusing on Carrier Aggregation, and identifies and evaluates the physical layer requirements that LTE needs to meet for functioning in the unlicensed spectrum. Carrier Aggregation allows the merging of separate carriers in order to increase bandwidth, so that the bitrate is increased, and it allows simultaneous use of licensed and unlicensed spectrum.

It had the important role in defining the requirements LAA needs to fulfill such as interference from LAA to the Wi-Fi services should not be higher than the interference caused by another Wi-Fi network.

Based on the design targets of the 3GPP feasibility study on LAA [3] the following functionalities are required for LAA:

- Listen Before Talk or LBT, which is similar to Clear Channel Assessment in Wi-Fi
- Discontinuous transmission on a carrier with limited maximum transmission duration
- Dynamic frequency selection (DFS) for radar avoidance in certain bands/regions[1]
- Carrier selection
- Transmit Power Control

This "Study Item" considers the carrier aggregation operation between a primary LTE carrier in the licensed spectrum and one or more low power secondary carriers that operate in the unlicensed spectrum. The deployments scenarios cover the cases for with and without macro coverage, outdoor and indoor small cell deployments, co-location and non-co-location (with ideal backhaul) between the licensed and unlicensed carriers.

In the deployment scenarios, the backhaul between the small cells can be ideal or non-ideal[2], but the unlicensed small cell only operates in the context of carrier aggregation through the ideal backhaul with a licensed cell [3]. In the cases where the carrier aggregation is operated within the small cell with carriers in both the licensed and unlicensed bands, the backhaul between the macro cell and small cell can be ideal or non-ideal.

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[1] DFS is a procedure for allowing devices in unlicensed spectrum to use the 5 GHz frequency bands that are already allocated to radar systems in Europe, USA and other areas [46].

[2] Ideal backhaul implies that there is very high throughput and very low latency (e.g., dedicated point-to-point connection using optical fiber). Non-Ideal backhaul implies using an existing wired connection such as xDSL (Digital Subscriber Line), microwave, and other backhauls like relaying [47].

Regarding the modes of operation, the unlicensed spectrum can be used only for carried aggregation (CA) only for Downlink and for both Uplink and Downlink. Release 13, only defines Carrier Aggregation for Downlink.

Figure 2 shows these four possible deployment scenarios for LAA.

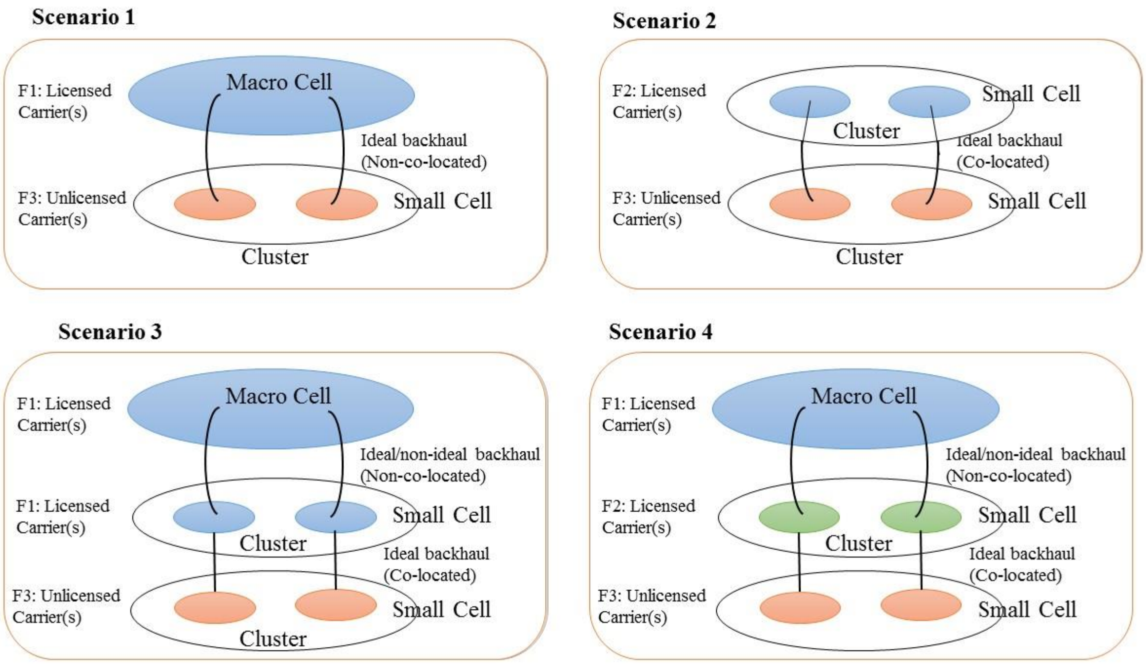

Figure 2. LAA deployment scenarios based on [3]

These scenarios are briefly described below:

Scenario 1

Carrier aggregation between licensed macro cell (F1) and unlicensed small cell (F3)

Scenario 2

Carrier aggregation between licensed small cell (F2) and unlicensed small cell (F3) without macro cell coverage

Scenario 3

Licensed macro cell and small cell (F1), with carrier aggregation between licensed small cell (F1) and unlicensed small cell (F3)

Scenario 4

Licensed macro cell (F1), licensed small cell (F2) and unlicensed small cell (F3)

- Carrier aggregation between licensed small cell (F2) and unlicensed small cell (F3)
- If there is ideal backhaul between macro cell and small cell, there can be carrier aggregation between macro cell (F1), licensed small cell (F2) and unlicensed small cell (F3)
- If dual connectivity is enabled, there can be dual connectivity between macro cell and small cell. Dual connectivity allows user devices to receive data simultaneously from different eNodeBs.

2.2.2.1 Listen before Talk

In countries, other than United States, China and South Korea, there is a regulatory requirement to "Listen-Before-talk", or to implement the LBT algorithm. LBT is one of the required functionalities of LAA because it ensures fair sharing for the 5GHz band. When LBT is implemented, each node that operates at a given location will scan the channel to see if there is any activity in this channel. It will only transmit when it finds that the channel is available. This way multiple technologies can use the same spectrum.

LBT uses the ED (Energy Detect Threshold) to sense for other technologies. If the node does not sense any signal based on the ED threshold, then the node can go ahead with the transmission - CCA (Clear channel LBT assessment). But if the node finds the channel busy, then it will wait until the channel becomes available – eCCA (Extended CCA). When the channel is clear, the node will wait for a random number of additional CCAs to make sure that the channel has remained clear before starting transmission [4]. The above explained procedure can be seen in Figure 3.

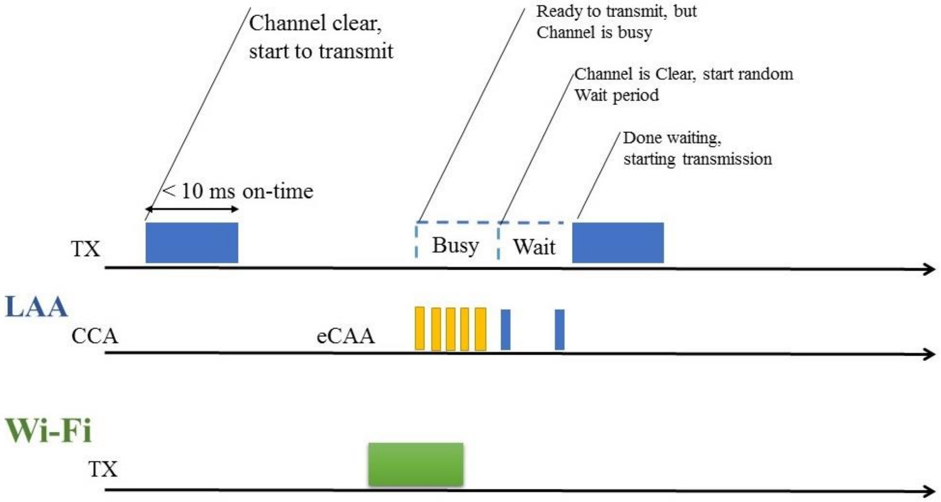

Figure 3. LAA with LBT based on figure from [4]

2.2.3 LWA

LTE Wi-Fi Aggregation (LWA) is a new alternative for LTE and Wi-Fi interworking. It consists of data aggregation at the radio access network, where an eNodeB (the base station in LTE) schedules the packets that are to be served on both LTE and Wi-Fi radio links. This is like the features in Release 10 and 12 about carrier aggregation and dual connectivity, but with the advantage that it can provide better control and utilization for both links. This has the potential to increase the aggregate throughput for all the users, and improve the overall system capacity. The data aggregation at the RAN (Radio Access Network) can be implemented without changing anything in the core network, because the WLAN radio link will be part of the E-UTRAN [48].

2.2.4 Multefire

Qualcomm together with other companies such as Ericsson, Inter and Nokia have come with a new proposal for the LTE in the unlicensed spectrum, which does not require a licensed primary channel. The main objective of Multefire is to provide the best user experience for wireless access to the Internet, and particularly in dense deployments. It will accomplish its goal by combining the advantages of LTE with the simplicity of Wi-Fi-like deployments.

Just recently, the Multefire Alliance released the first guideline for MulteFire Specifications. The design objective for Multefire, is to mainly reuse the existing LTE architecture defined in 3GPP. The changes in the LTE architecture will depend on the deployment scenario [32]. Since Multefire is still new, and was not included in the comparison of this work, further details are not presented in this thesis.

2.3 RELATED WORK

In recent years, there are some existing studies evaluating the coexistence of Wi-Fi and LTE in the unlicensed spectrum. In [5] and [6], through experimental analysis, the authors confirm that LTE significantly impacts Wi-Fi performance in different environment scenarios. In [5] the results show that small bandwidth of LTE-LAA (1.4, 3, 5, 10 MHz) has a higher impact on Wi-Fi throughput (e.g., the throughput drops from 35 Mbps almost to zero). The work in [6] shows that the frequent on and off switching of LTE causes Wi-Fi to sense the medium as busy and thus halt transmissions. In [7] - [9], through simulation and theoretical analysis, the fairness allocation between Wi-Fi and LTE-LAA is evaluated. In [10] – [18], different coexistence mechanisms between Wi-Fi and LTE-

U are proposed, and, [10] – [12] introduce the Listen Before Talk (LBT) algorithm to be implemented in LAA. The different deployment scenarios for LAA are proposed in [19,20].

The coexistence of Wi-Fi and LTE considering different indoor office scenarios were investigated in a simulation study [21]. The results showed that the Wi-Fi performance degraded heavily when sharing the unlicensed band with LTE. In [22] it is shown that when two LAA networks coexist, the aggregate throughput is larger than when two Wi-Fi networks coexist. Furthermore, when LBT algorithm is implemented in LAA, and LAA coexists with another Wi-Fi network, again the aggregate throughput is higher compared to the case when two Wi-Fi networks operate in the same channel.

In [23,24], to evaluate the coexistence of Wi-Fi and LAA experimental and simulation studies are carried out. From the experimental results, it is concluded that in the case of a single Wi-Fi access point and one LTE LAA eNodeB, LAA performs better than Wi-Fi in both coverage and throughput.

Different coexistence mechanisms between Wi-Fi and LTE are proposed in [10-18]. A contention based algorithm for LAA was introduced in [10-12]. In [15] multiple LTE coexistence mechanisms are proposed. From the simulation results, LTE gains throughput performance without degrading the performance of coexisting Wi-Fi networks. In [25] a framework is proposed for the coexistence of LTE and Wi-Fi. The simulation results show that the framework can shield the Wi-Fi performance from the LTE interference. In the simulation study [26] the coexistence between LTE and Wi-Fi has been evaluated in the TV White space band. The results show that even when Wi-Fi and LTE nodes are randomly positioned, the LTE interference degrades the Wi-Fi performance.

Another mechanism to improve the coexistence of LTE with Wi-Fi is proposed in [27]. In that mechanism, the LTE transmit power is reduced gradually to create more transmission chances for Wi-Fi. Yet another study [19], carried out simulations where multiple operators would be using the same unlicensed band. In the 2-operator case, the results show that the user performance would degrade due to the different eNodeB deployments.

Qualcomm in [28-30] did some evaluation studies of the Wi-Fi and LAA coexistence. The main LTE advantages over Wi-Fi are identified to be better coverage and increased capacity. LTE can provide higher quality services than Wi-Fi, for the same transmit power. In their studies, it has been concluded that it is possible to achieve a two times higher performance with LAA than with Wi-Fi.

To evaluate the coexistence performance of Wi-Fi and LAA based on different deployment scenarios, the work in [31] runs simulations while implementing the LBT algorithm. From the results, it can be seen that the coexistence performance varies based on the deployment. In sparse deployments, there is not a big difference in the throughput of Wi-Fi when coexisting with LAA. However, in dense deployments, the Wi-Fi throughput drops when coexisting with LAA.

In the next chapters, we compare these research papers in more detail. That is the primary objective of this thesis.

3.0 CLASSIFICATION OF STUDIES

A comparative evaluation of the impact of using LTE in unlicensed spectrum is considered in this chapter. To evaluate the performance of LAA and LTE-U, the results of 17 studies were collected and compared. The chosen studies deal with the coexistence of Wi-Fi and the different LTE versions in the unlicensed spectrum. The data for comparison were obtained by approximating the values from the plots presented in the various papers.

3.1 FACTORS

To classify the studies, multiple factors were taken into consideration.

Firstly, we consider the *operating frequency band* of LTE-U/ LAA. Since some studies were conducted before it was established that LAA and LTE-U are going to operate in the 5GHz band, during their experiments/simulations they used different operating frequency bands. Different frequency bands, means different "Path Loss" models (how much the signal strength drops with distance). In general, the higher the frequency, the signal propagation distance is shorter (for a given transmit/received power). Thus, the interference is smaller.

The next parameter is the *deployment scenario*, whether indoor, outdoor or mixed. The two environments are affected differently by "Path Loss" and experience varying levels of interference.

Finally, the studies were separated based on whether they used *coexistence mechanisms* (e.g. LBT) for their experiments or not. The studies carried out before the LAA "Study Item", present the results of plain coexistence between LTE and Wi-Fi networks in the unlicensed band.

The studies implementing LBT algorithm report a lower interference towards the Wi-Fi networks, compared to LTE operating without LBT.

After it was established that the LBT algorithm is a requirement for LAA, the various papers considered in this thesis, present the data when Wi-Fi coexists with another Wi-Fi network, Wi-Fi coexisting with LTE in the same frequency band when LTE implements a coexistence mechanism, and LAA/LTE-U coexisting with another LAA/LTE-U network.

The basic simulation parameters that were considered by the papers during the collection of results are:

- The transmission power of LTE eNodeB-s: The Transmission power (Tx) varies from 18 dBm for indoor environments to 30 dBm for outdoor environments.
- The size of the indoor environments: Generally, for all studies the parameters for indoor deployments were 100m × 50m and 120m × 50m.
- The number of channels shared between LTE and Wi-Fi: Mostly, they shared a 20 MHz channel in the 5 GHz band.
- The CCA (Clear Channel Assessment) threshold. In most papers, the CCA is at -82 dBm or -62 dBm. The exception is one study, where one of the study’s goals was to see the impact of different CCA thresholds.

3.2 DESCRIPTION OF PAPERS

The papers used for comparison are as described below.

Firstly, they are divided into two groups based on the operating frequency: The 900 MHz frequency band and the 5 GHz frequency band. Conveniently, the study using the 900 MHz operating frequency band is conducted before the LAA “Study Item”, and presents the plain performance when coexistence between Wi-Fi and LTE in the unlicensed spectrum is considered.

The next division is based on whether they consider LTE-U systems or LAA systems. Even though LTE-U is the first approach to introduce LTE in the unlicensed bands, the development halted and the number of studies considering LTE-U is small. One factor for this could be the fact that LTE-U does not require the implementation of the LBT algorithm, and a global solution will need LBT because of regulatory requirements in most of the countries. For LTE-U, one paper did the simulations without implementing coexistence mechanisms and a second paper depicts the performance of LTE-U systems after implementing the coexistence mechanisms ([34] and [35], respectively).

The number of LAA papers is higher and the deployment scenarios they use are defined in [3] the 3GPP LAA “Study item”. They are divided based on whether the environment is Indoor or Outdoor, and then whether the LAA network implements the LBT algorithm or not. Only one study conducted their simulations for the operating frequency band of 900 MHz., while the others did their simulations/experiments in the 5GHz band. The classification can be seen in Figure 4 below.

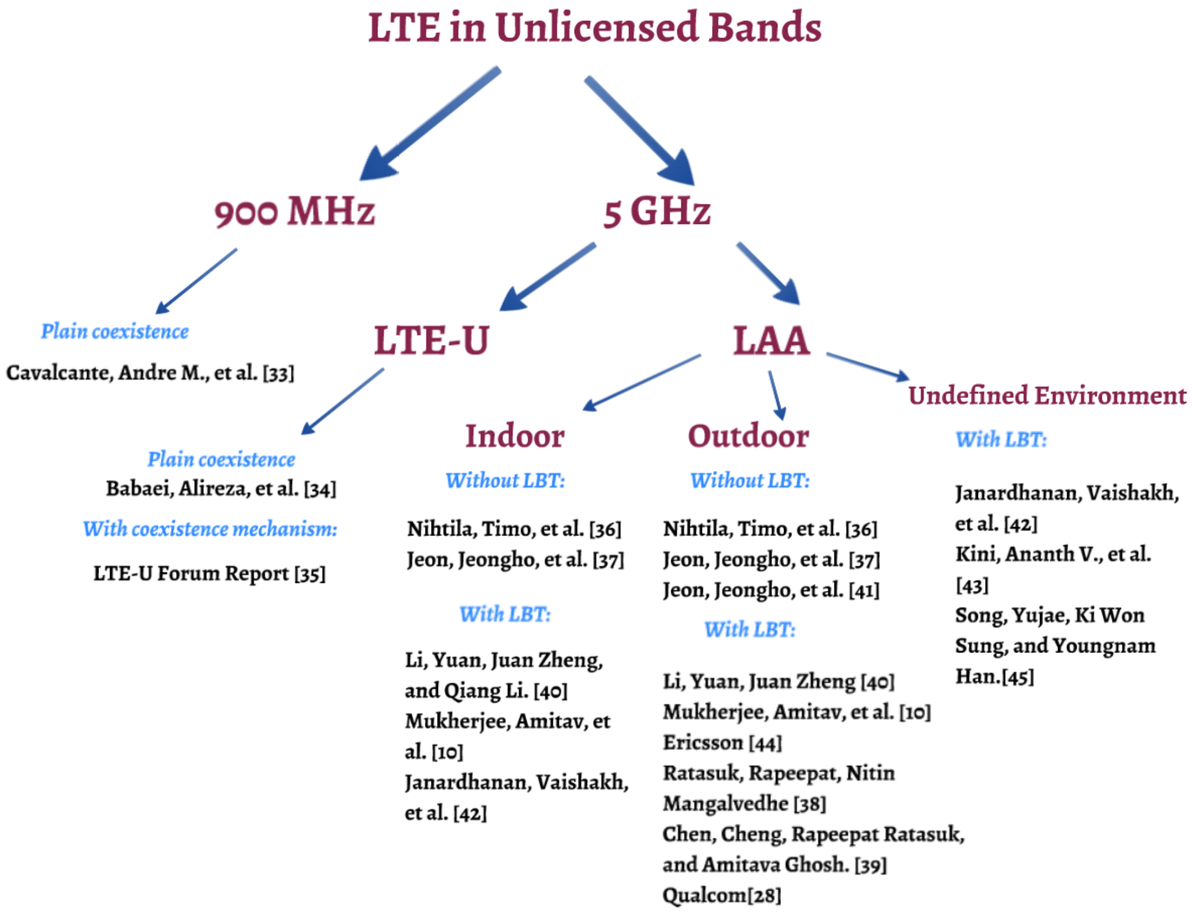

Figure 4. Classification of studies

3.3 LTE-U IN THE 900 MHZ UNLICENSED BANDS

The one simulation study by **Cavalcante, Andre M., et al. [33]** was published in 2013, the same year 3GPP Rel 10 was released and 2 years before 3GPP Rel 12. The operating frequency for introducing LTE in the unlicensed bands was still unknown and they used the 900MHz frequency band.

The study evaluates the plain coexistence of LTE and Wi-Fi in a multi-floor office environment. Plain coexistence means, the two technologies share the same frequency channel without any coexistence mechanism implemented on LTE. The results are presented first for one floor only, and then compared with the simulation results of the multi-floor scenario.

For the first scenario, the floor is of size 100m × 20m, and contains 20 rooms. Two cases were considered: Sparse Deployment with 4 Access Points (APs) per system (Wi-Fi/LTE) distributed in the floor and the Dense Deployment case with 10 APs per system. The second scenario considered 3 different cases: Sparse Deployment with one AP per system, Moderate Deployment with 2 APs per system and Dense deployment with 5 APs per system. The results are summarized in Table 1 & Table 2.

The LTE performance in the first scenario is very close to the LTE standalone performance (LTE operating without sharing the same frequency band with Wi-Fi). The highest reduction it suffers is 3.85% for both Sparse and Dense deployment cases.

Table 1. User throughput (Mbps) performance for the single-floor scenario: Sparse deployment

	4 APs/10 STAs per system	4 APs/25 STAs per system
LTE only	23.4	8.6
Wi-Fi only	6.1	2.6
LTE coex.	22.5	8.6
Wi-Fi coex.	1.4	0.8

Table 2. User throughput performance (Mbps) for single-floor scenario: Dense deployment

	10 Aps/10 STAs per system	10 Aps/25 STAs per system
LTE only	32.2	14.1
Wi-Fi only	8	3.4
LTE coex.	32.2	13.6
Wi-Fi coex.	0.27	0.06

In the sparse deployment case, Wi-Fi suffers a reduction higher than 98% in the case of 10 APs/25 STAs. For the dense deployment, the results show an even higher reduction of Wi-Fi performance. This happens because the Wi-Fi nodes stay on Listen Mode for around 99% of the time [33].

The multi-floor scenario results (see Table 3) also shows a severe degradation of the Wi-Fi performance in coexistence mode. The reduction of Wi-Fi performance goes from 70% in sparse deployment to almost 100% for the dense deployment. The LTE performance again suffers a small reduction due to the coexistence, but the reduction is always lower than 4.5%.

Table 3. User Throughput (Mbps) performance for multi-floor study cases

	1 APs/2 STAs per system per floor	2 APs/4 STAs per system per floor	5 APs/10 STAs per system per floor
LTE only	34.1	26.4	20
Wi-Fi only	9.1	6	3.1
LTE coex.	34.1	25.8	19.1
Wi-Fi coex.	2.725	0.587	0.002

The study found that because of carrier sensing the Wi-Fi nodes stay on Listen mode for more than 96% of the time of the simulations. LTE on the other hand, does not implement scanning to check whether a channel is available before transmissions, hence the Wi-Fi transmission was blocked for most of the time as expected.

3.4 LTE-U PAPERS

In this section, we consider the papers that evaluate the performance of LTE-U.

To evaluate how much LTE-U affects the Wi-Fi performance, a study by **Babaei, Alireza, et al. [34]** took an analytical approach by taking into consideration two proposed configurations for LTE-U by 3GPP. The two proposed configurations are:

- Supplemental Downlink (SDL) and
- Carrier Aggregation TD-LTE (time-division duplexing)

The analytical analysis did not define the environment scenario to be indoor or outdoor. Their probabilistic and numerical results showed that the probability of Wi-Fi to access the channel is heavily impacted by the LTE transmission. Thus, one way of allowing Wi-Fi to access the channel is to have LTE-U "quiet periods" or *muting*.

The maximum "quiet period" for LTE that can be created by *muting* the uplink sub-frames in TD-LTE mode is 3 milliseconds. The results show that even if LTE-U is muted for a period of 3ms, and the number of Wi-Fi access points is as low as 2, the probability that the Wi-Fi back-off delay is smaller than the LTE-U quiet period is 0.16.

Thus, the probability that a Wi-Fi node can access the channel while sharing the channel with LTE-U is about 16% in the best-case scenario. Even the maximum quiet period for LTE is insufficient for the Wi-Fi users to access the channel. The analytical study concludes that the LTE MAC layer must change for coexistence to be achieved.

The next work we describe is based on the **LTE-U Forum Report [35].**

The LTE-U forum presented the LTE-U Forum Report, which includes performance evaluation of Wi-Fi coexisting with LTE-U. The report presents data for different scenarios but for this work, in order to make the comparison of the papers easier, only the results from similar simulation setups were considered. In the report, LTE-U implements coexistence solutions that are recommended for non LBT markets. The recommended coexistence mechanisms were briefly described in section 2.2.1.

Table 4. Object Data Rate Per User (Mbps) for 2 operators' low density deployment

		Total served traffic per operator and macro cell [Mbps]					
		160	200	300	400	500	600
Wi-Fi coexists with Wi-Fi	Wi-Fi A 5th percentile	50	35	10	5	NA	NA
	Wi-Fi A mean	140	125	85	50	NA	NA
	Wi-Fi B 5th percentile	40	25	10	5	NA	NA
	Wi-Fi B mean	145	125	85	45	NA	NA
LTE-U coexists with LTE-U	LTE A On/Off 5th percentile	70	65	40	25	15	10
	LTE A On/Off mean	200	190	160	130	100	75
	LTE B On/Off 5th percentile	65	50	37	25	15	10
	LTE B On/Off mean	195	180	145	120	80	50
Wi-Fi coexists with LTE-U	LTE A On/Off 5th percentile	50	48	25	15	10	5
	LTE A On/Off mean	180	175	140	100	60	48
	Wi-Fi B 5th percentile	30	25	15	10	5	NA
	Wi-Fi B mean	150	125	80	45	NA	NA

The evaluation of the system capacity is done by collecting user throughput statistics under different served traffic loads. The macro-cells are the larger LTE cells and the smaller cells use LTE-U.

The system capacity results are presented for the outdoor scenario where two operators share 10 Frequency elements. For each operator, there are 4 small cells deployed in each macro cell for providing offloading. From Table 4, in the case of two operators using Wi-Fi offloading, if the operators target a cell-edge user MAC layer throughput of 5 Mbps, then each macro cell is able to carry 250Mpbs of traffic. In the case where both operators use LTE-U for offloading, then for the same targeted cell-edge user throughput, each macro cell can carry more than 500Mbps of traffic.

For the case where LTE-U coexists with Wi-Fi with coexistence mechanisms, one operator uses LTE-U offloading and the other performs Wi-Fi offloading. The results show that in each macro cell Wi-Fi still can carry 250 Mbps of traffic and LTE-U is able to carry more than 500 Mbps.

When Wi-Fi coexists with another Wi-Fi network, the mean Object Data rate per User[3] is 140 Mbps. When One Wi-Fi node is replaced with LTE-U, the mean Wi-Fi Object Data rate per user is increased to 150 Mbps. Which shows that LTE-U acts as a "better" neighbor to Wi-Fi than Wi-Fi itself. The LTE-U performance suffers a minor decrease but at the cost of providing same transmission opportunities to Wi-Fi. Similar results can be seen from Figure 5 and Figure 6 below.

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[3] Object Data Rate per User measures the traffic carrying capacity of different systems (e.g. Wi-Fi/LTE systems) per user [35].

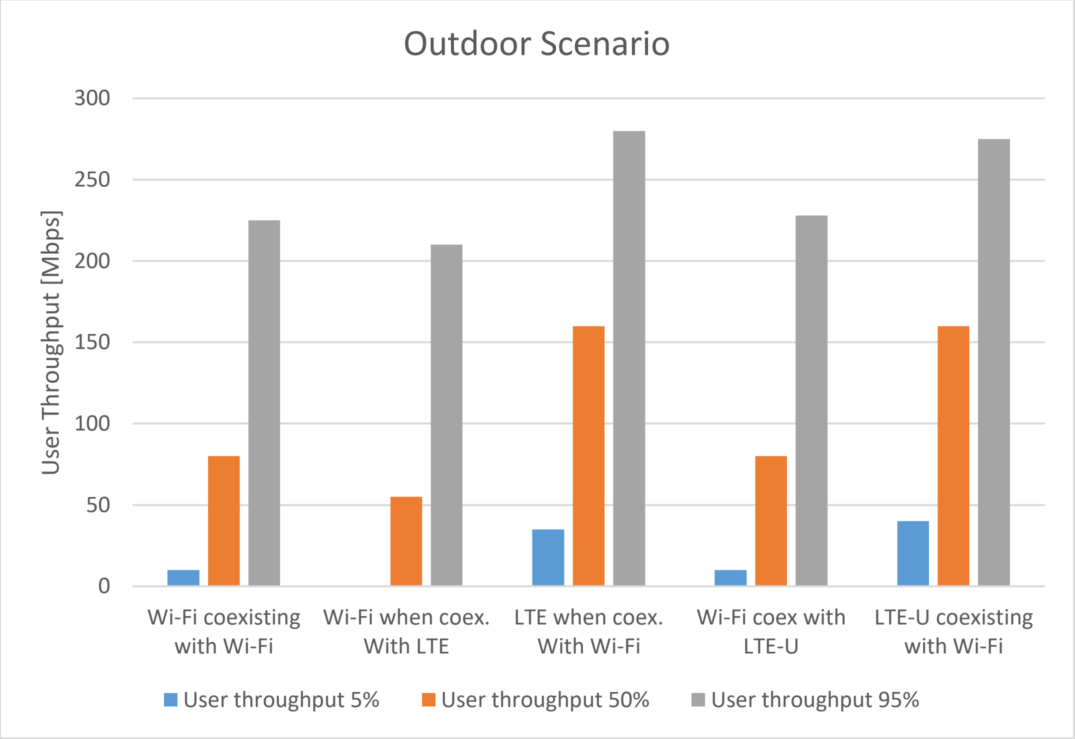

Figure 5. LTE-U and Wi-Fi performance for the Outdoor Scenario for different user throughput loads.

In Figure 5 we see that for loads of 95%, Wi-Fi coexisting with another Wi-Fi achieves up to 225 Mbps. But when Wi-Fi is coexisting with LTE-U, user throughput increases to approximately 230 Mbps. This is a slight increase but important when compared with the previous paper [34] not taking into consideration coexistence mechanisms.

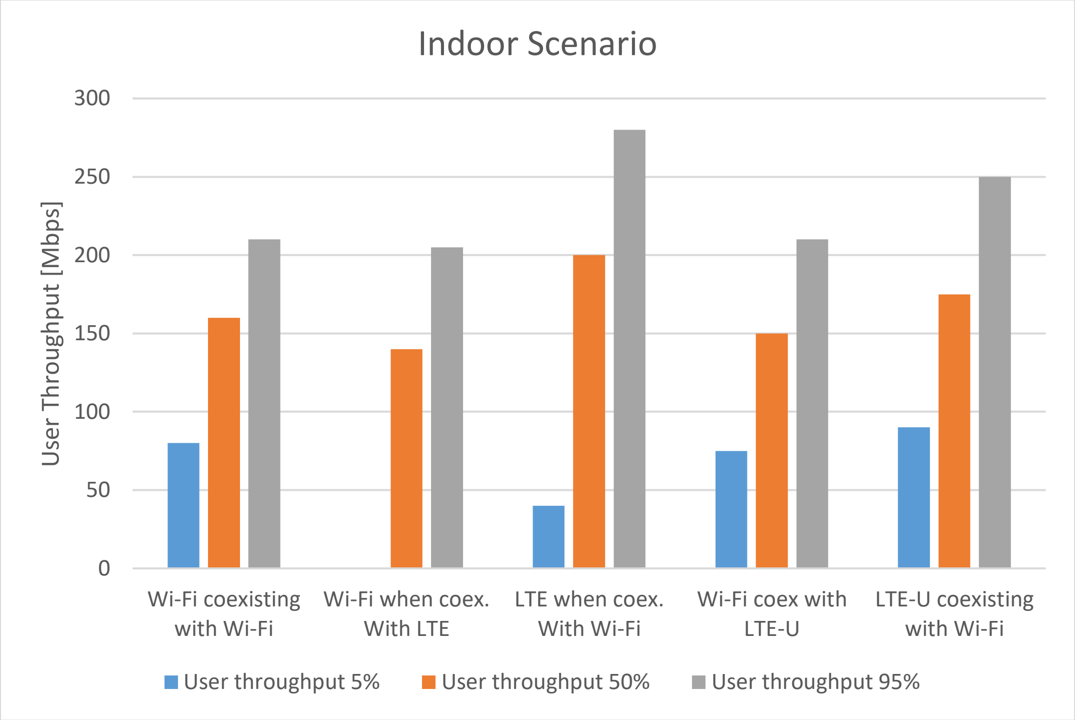

Figure 6. LTE-U and Wi-Fi performance for the Indoor Scenario

In Figure 6, we observe a similar trend where the Wi-Fi performance improves from 210 Mbps when coexisting with another Wi-Fi node to 212 Mbps when coexisting with LTE-U as a neighbor (very slight improvement). Thus, by comparing the LTE-U forum paper [35] and Babaei, Alireza, et al. [34] we see that without coexistence mechanisms Wi-Fi performance drops, while when coexistence mechanisms are implemented in LTE-U the Wi-Fi performance improves slightly for 2-5 Mbps, but more importantly it has the same chance of transmitting as LTE-U.

3.5 LAA PAPERS

3.5.1 Baseline scenario papers

The first paper we consider with LAA is that by **Nihtila, Timo, et al. [36].** Before LAA together with the coexistence mechanisms was defined, Nihtila, Timo, et al. [36] conducted simulations to measure the LTE and Wi-Fi performance while they are sharing the same frequency channel and while implementing different channel access mechanisms.

The simulation setup is an indoor office of 100m × 50 m. 6 Wi-Fi APs and 6 eNodeBs are positioned in separate rooms within the building to ensure an even interference between the networks. Users are created with a uniform spatial distribution, and they are stationary through the simulations. The channel bandwidth is 20MHz and the transmit power for both the eNodeB and Wi-Fi AP is – 20dBm.

The paper's results compare the performance of LTE and Wi-Fi. In the Standalone cases, with the increased offered load, both systems observe increases in the served load. But at higher loads, LTE performs better clearly since the load is increased by adding more users to the network, and in this case LTE generally performs better than Wi-Fi.

When both LTE and Wi-Fi share the same band without any techniques to handle the coexistence, it can be seen that LTE performance slightly drops compared to the standalone case, while the Wi-Fi performance drops significantly (See Table 5). This degradation can be controlled by restricting the LTE activity with a muting scheme, where the LTE eNodeBs follow a muting scheme and this way give Wi-Fi the opportunity of transmitting in the medium.

Table 5. LTE and Wi-Fi performance, Standalone and shared frequency band cases

Offered Load per technology per cell [Mbps]		10	20	30	40
Served Load per cell [Mbps]	Standalone LTE performance	10	20	30	37
	Standalone Wi-Fi performance	10	14	15	17
	LTE performance on a shared band	10	19	26	33
	Wi-Fi performance on a shared band	7	4	2	1
	Combined performance on a shared band	16	23	30	34

Next the paper presents results when LTE is restricted from transmitting for a time by using the *fractional allocation bandwidth* method so that Wi-Fi has more chances to transmit. The results present the performance of LTE when LTE muting is implemented, Wi-Fi performance and the combined performance.

Table 6. LTE performance with LTE muting

		Offered Load per technology per cell [Mbps]			
		10	20	30	40
Served Load per cell [Mbps]	LTE performance, LTE muting:0%	10	20	27	32
	LTE performance, LTE muting:20%	10	18	24	27
	LTE performance, LTE muting:40%	10	16	19	21
	LTE performance, LTE muting:60%	10	12	13	13
	LTE performance, LTE muting:80%	6	6	6	6
	LTE performance, LTE muting:100%	0	0	0	0

The LTE performance drops with the increase of LTE muting quite linearly as observed in Table 6, while the Wi-Fi performance increases. In Table 6, we see that for a 20 Mbps offered load, until a 60% level of muting is taken into consideration, the LTE performance suffers mildly. The

Wi-Fi performance is improved (Table 7) with the increase of muting % of LTE, while the combined performance is decreased. The combined performance decreases because the LTE system throughput has a higher weight into the combined performance (Table 8).

Table 7. WLAN performance with LTE muting

		Offered Load per technology per cell [Mbps]			
		10	20	30	40
Served Load per cell [Mbps]	Wi-Fi performance, LTE muting:0%	6	4	2	1
	Wi-Fi performance, LTE muting:20%	6	5	4	4
	Wi-Fi performance, LTE muting:40%	6	5	5	5
	Wi-Fi performance, LTE muting:60%	6	7	8	9
	Wi-Fi performance, LTE muting:80%	8	10	11	12
	Wi-Fi performance, LTE muting:100%	10	13	14	15

Table 8. Combined performance with LTE muting

		Offered Load per technology per cell [Mbps]						
		10	20	30	40	60	70	80
Combined Served Load per cell [Mbps]	Combined performance, LTE muting:0%	8	16	19	23	28	32	34
	Combined performance, LTE muting:20%	8	16	19	23	27	30	31
	Combined Wi-Fi performance, LTE muting:40%	8	16	19	22	24	25	26
	Combined Wi-Fi performance, LTE muting:60%	8	16	17	20	21	21	22
	Combined Wi-Fi performance, LTE muting:80%	8	15	16	16	17	17	17
	Combined Wi-Fi performance, LTE muting:100%	5	10	11	13	14	15	15

Next we consider the work in **Jeon, Jeongho, et al. [37].** By 2014, it was clear that for LTE to be deployed in the unlicensed spectrum, coexistence mechanisms need to be implemented. But which coexistence mechanisms would be required were not defined. Jeon, Jeongho, et al. [37] is a simulation study that compares different coexistence mechanisms in a single framework. The study did two deployment scenarios: outdoor and a mixed outdoor/indoor scenario.

In the **outdoor** deployment, LTE eNodeB is located at the center, and around the eNodeB are 3 Wi-Fi AP. The cell radius is 100 m and the number of user devices and stations changes during the simulation.

For the **indoor/outdoor** deployment, the Wi-Fi APs are located in separate buildings of size 40m × 40 m. In every cell, 20% of the user devices are located outdoor while the rest 80% are in the 3 buildings where the Wi-Fi APs are located. LTE and Wi-Fi share a 20 MHz channel at 5.8 GHz, with transmit powers of 30 dBm and 20 dBm, respectively. The CCA threshold is set at -82 dBm and only the size of the contention window (CW) is changed.

After analyzing various LTE muting schemes, it was seen that the combined performance for LTE and Wi-Fi is best with a successive asynchronous pattern for both deployment scenarios. That is why it is chosen for comparison with the other coexistence mechanisms [37].

The results from the simulations, summarized in Table 9 showed like many studies before, that the two technologies cannot coexist without additional mechanisms when both nodes are located outdoor. When the Wi-Fi node is indoor, the performance is not much impacted by the eNodeBs located outdoor because of the high penetration loss.

Table 9. Comparison for the Outdoor scenario at 30 Mbps offered load per LTE cell/WLAN BSS

Served Load [Mbps]	LTE	Wi-Fi
Standalone	27.74 (100%)	10.28 (100%)
Plain Coexistence	21.45 (77%)	1.88 (18%)
Muting	13.87 (50%)	3.66 (36%)
LBT	11.22 (40%)	4.82 (47%)
Self-CTS	10.02 (36%)	5.04 (49%)
RTS/CTS	11.62 (42%)	5.01 (49%)

When the user devices coexist with the Wi-Fi node in the same indoor environment, they are affected by the hidden node problem because the sensing at the outdoor eNodeB does not function well. In this case the RTS/CTS coexistence mechanism is suggested to be a better solution compared to the other coexistence mechanisms because it solves the hidden node problem most effectively.

Table 10.Comparison for the Indoor/Outdoor mixed scenario at 30 Mbps offered load per LTE cell/WLAN BSS

Served Load [Mbps]	LTE	Wi-Fi
Standalone	16.33 (100%)	28.73 (100%)
Plain Coexistence	9.67 (59%)	27.66 (96%)
Muting	8.71 (53%)	28.39 (99%)
LBT	8.48 (52%)	28.17 (98%)
Self-CTS	9.39 (58%)	21.75 (76%)
RTS/CTS	12.18 (75%(	26.02 (91%)

In the **outdoor scenario,** the system performance of Wi-Fi when coexisting with LTE is significantly decreased from 10.28 Mbps to 1.88 Mbps. From Table 9 it can be seen that even with the LBT mechanism the Wi-Fi performance is reduced by half, compared to the standalone case of Wi-Fi. LTE significantly outperforms Wi-Fi and this difference is reduced with the implementation of the coexisting mechanisms. The most effective coexistence mechanism is found to be RTS/CTS; the system performance of Wi-Fi is 49% while for LTE, it is 42% which shows the effectiveness of the mechanism in achieving almost equal channel access.

In the **indoor/outdoor** mixed scenario (see Table 10)**,** the effect of RTS/CTS mechanism implemented is even more notable. The Wi-Fi system with RTS/CTS maintains 91% of its performance, while LTE keeps 75% of its performance. Part of the reason for this smaller difference than in the outdoor scenario, is due to the reduced interference from LTE, because of the penetration loss for indoor areas.

Next, we describe an analytical work done in **Jeon, Jeongho, et al. [41]**, which is the last paper we consider that presents the plain coexistence between Wi-Fi and LAA.

To analyze the interference caused when multiple different technologies coexist in the same frequency band, this study created an analytical tool inspired by the fluid network model. The interference was analyzed when no coexistence mechanisms were implemented, and the LTE cell radius differs from 30 m to 300 m. The results are presented for both LTE and Wi-Fi performance.

From the results in Table 11 below, it can be seen that the LTE cell radius of 90 m maximizes the LTE system throughput.

Table 11. LTE performance as a function of the Cell Radius

		LTE cell radius					
		30 m	90 m	120 m	180 m	240 m	300 m
Sum throughput per cell (Mbps)	LTE-only	76	100	98	80	65	53
	LTE-Wi-Fi coexist	75	68	55	38	28	22
Coexistence/LTE-only (%)	LTE throughput loss due to the coexistence	98	67	55	46	43	41

This optimal cell size is reduced to 80 m when LTE coexists with the Wi-Fi systems. This can be explained by the two effects of reducing the cell size: reducing intersystem interference (by blocking more Wi-Fi nodes) and increasing the intra-system interference (due to the decreased inter-eNodeB distance).

Table 12. Wi-Fi performance as a function of LTE cell radius

		LTE cell radius					
		30 m	90 m	120 m	180 m	240 m	300 m
Wi-Fi Sum Throughput	Wi-Fi only	138	138	138	138	138	138
	Wi-Fi - LTE coexistence	5	38	50	70	88	98

When only LTE is implemented the highest throughput for LTE is achieved for a cell radius of 90 m. While when LTE coexists with Wi-Fi the optimal cell radius is 30 m. The Wi-Fi throughput when the two technologies coexist, is the highest for 300 m LTE cell radius (see Table 12). Because the interference from LTE is much smaller at this distance. When LTE performs best during coexistence, the Wi-Fi throughput is a mere 5 Mbps compared to LTE throughput 75 Mbps.

3.5.2 Studies considering LBT algorithm

The first paper we consider that implements the LBT algorithm is **Ratasuk, Rapeepat, Nitin Mangalvedhe, and Amitava Ghosh [38].** This simulation study focuses on LAA implemented in the form of Supplemental Downlink, and only for the case of coexistence between LAA with LAA (i.e., two LAA networks). The performance of the system is evaluated for three different scenarios:

- Indoor hotspot
- Indoor office and
- Outdoor small cell deployment

For the **indoor hotspot scenario**, there are 2 eNodeBs located in an open floor of size 120m×50m. The LTE transmission power is 20 dBm.

For the **indoor office scenario**, there are a larger number of eNodeBs. There are six eNodeBs located within a floor of size 110m x 50m. Lastly, for the **outdoor scenario**, there are 10 eNodeBs located within an area of 500m x 500m. The transmission power: 30 dBm.

Table 13. Downlink system throughput (Mbps) for indoor hotspot scenario.

		Offered Load per cell =80 Mbps	Offered Load per cell =140 Mbps
1 Operator	No. of Channels=2	80	130
	No. of Channels=1	70	80
	No. of Channels=1, LBT	60	65

2 Operators	No. of Channels=1	40	50
	No. of Channels=1, LBT	40	50

The results in Table 13 show that for the **indoor hotspot scenario**, the highest downlink system throughput that can be achieved for LAA is 130 Mbps when two channels are used.

For one channel used, without LBT, the highest downlink system throughput that can be achieved is 80 Mbps, and with LBT is 65 Mbps. It is important to note that with the use of LBT scheme it is ensured that all users get service. For two operators, the downlink system throughput falls to 50 Mbps.

Table 14. Downlink system throughput (Mbps) for outdoor small cell scenario.

	Offered Load per cell =140 Mbps
No. of Channels=2	70
No. of Channels=2, LBT	50
No. of Channels=1	60
No. of Channels=1, LBT	40

Without the Listen Before Talk mechanism in the **indoor hotspot scenario**, 30% of users have zero throughput. These users struggle with high interference due to the lack of ability to connect to the strongest cell.

For the **indoor office scenario,** when LBT is implemented, LAA can provide downlink throughput per 20 MHz channel up to 60 Mbps. For low offered loads, 50% of the users can receive throughput up to 5 Mbps at least and 20% of the users receive throughput of at least 20 Mbps (see Table 15).

Table 15. Downlink system throughput (Mbps) for indoor office scenario.

		Offered Load per cell =80 Mbps	Offered Load per cell =140 Mbps
1 Operator	No. of Channels=6	80	110
	No. of Channels=2	70	95
	No. of Channels=1	63	80
	No. of Channels=1, LBT	50	60
2 Operators	No. of Channels=1	40	60
	No. of Channels=1, LBT	35	40

For the **outdoor small cell scenario** (see Table 14**),** the results are similar to the other scenarios, with the highest downlink system throughput: 70 Mbps for two channels. For one channel with LBT the value is 40 Mbps. This study concludes that the LBT scheme is necessary to provide all users a fair share of service.

Next we present the work in **Chen, Cheng, Rapeepat Ratasuk, and Amitava Ghosh. [39].** This work proposes an analytical framework based on Markov chains to analyze the coexistence performance of LAA and Wi-Fi. The study considers the same coexistence scenarios for LAA coexisting with another LAA network, and Wi-Fi coexisting with LAA, where LAA implements a simple LBT scheme proposed in [38].

The simulation measurements are conducted for two operators sharing a 20 MHz channel in the 5.8 GHz band. There are 4 small cell eNodeBs/APs per operator, positioned uniformly within the cluster for the outdoor scenario, and deterministically for the indoor scenario. The 3GPP FTP (file transfer) traffic model is used with 0.5 MB file size and different Poisson based packet arrival rates.

The coexistence performance between the systems is compared for a fixed CCA threshold of -70 dBm and the proposed adaptive LBT scheme.

The **first scenario** considers the coexistence between two LAA eNodeBs. The analytical results coincide with the simulation results from the **indoor hotspot scenario** in [38]. They show that each eNodeB has approximately a 50% chance of successfully transmitting packets. This fair chance of transmission is achieved through the simple LBT scheme implemented which acts like a TDM system.

The **second scenario** considers the coexistence between LAA and Wi-Fi with and without LBT. When LBT is not implemented the results show an unfairness between LAA and Wi-Fi for high traffic loads. LAA dominates the channel, while the Wi-Fi system suffers from the interference and has little chance to access the shared channel. When LBT is implemented in LAA, the Wi-Fi performance is improved a lot compared to the case when LBT is not implemented in LAA, but still at high loads Wi-Fi suffers while the LAA performance does not. And when the number of access points and eNodeBs is increased, the co-existence becomes more problematic, with the channel access probability of Wi-Fi dropping to almost zero.

The next paper we describe that considers the LBT algorithm is **Li, Yuan, Juan Zheng, and Qiang Li. [40].** In this work, an enhanced LBT scheme was designed to improve the LAA throughput and guarantee coexistence with Wi-Fi. This was done by adjusting adaptively the CCA threshold to balance the channel access opportunity and interference avoidance.

For the simulations three scenarios were considered:

1. Wi-Fi of operator A coexists with Wi-Fi of operator B
2. Wi-Fi of operator A coexists with LAA of operator B
3. LAA of operator A coexists with LAA of operator B

In what follows, Adaptive LAA means that the LBT mechanism it implements, adjusts the CCA threshold adaptively contrary to the Fixed CCA Threshold, Fixed LAA respectively. Their results from the simulation show that LAA capacity gains can be achieved by using a more aggressive reuse with an acceptable increase of interference by configuring a moderately high CCA threshold.

Table 16. Average user perceived throughput (Mbps) of the proposed LBT scheme for Scenario 2 and Scenario 3 under outdoor deployment with Scenario 1 as a reference

	Packet Arrival rate (packets/sec)			
	0.4	0.6	1	1.2
Adapt, LAA: coexists with LAA	53	49	38	35
Adapt, LAA: coexists with Wi-Fi	24	19	12	6
Adapt, Wi-Fi: coexists with LAA	33	19	3	1
Fixed, LAA: coexists with LAA	43	35	18	9
Fixed, LAA: coexists with Wi-Fi	20	18	9	6

Fixed, Wi-Fi: coexists with LAA	32	23	3	1
Wi-Fi coexists with Wi-Fi	26	5	1	0.5

For the **indoor scenario,** the highest average user perceived throughput (UPT) is achieved when adaptive LAA coexists with another LAA node, for a packet arrival rate of 0.4 packets/sec the UTP is 58 Mbps This is in comparison to the **outdoor scenario**, from Table 16, where the highest UPT achieved is 53 Mbps.

The lowest UPT is achieved when Wi-Fi coexists with another Wi-Fi network, concluding that LAA not only is a good neighbor to another LAA network, but also a better neighbor to Wi-Fi than Wi-Fi itself.

For the indoor scenario, the highest UPT is again achieved when adaptive LAA coexists with another LAA. The difference between the UPT of LAA coexisting with LAA is almost 28 Mbps higher than when Wi-Fi is coexisting with another Wi-Fi network. These values are presented in Table 17 below.

Table 17. Average UPT (Mbps) of the proposed LBT scheme for Scenario 2 and Scenario 3 under indoor deployment with Scenario 1 as a reference

	Packet Arrival rate (packets/sec)			
	0.4	0.6	1	1.2
Adapt, LAA: coexists with LAA	58	54	47	40
Adapt, LAA: coexists with Wi-Fi	43	35	21	18
Adapt, Wi-Fi: coexists with LAA	40	30	10	8
Fixed, LAA: coexists with LAA	50	42	26	19

Fixed, LAA: coexists with Wi-Fi	40	30	20	17
Fixed, Wi-Fi: coexists with LAA	40	30	10	7
Wi-Fi coexists with Wi-Fi	35	15	2	1

Another paper to consider the LBT algorithm in LAA, is **Mukherjee, Amitav, et al. [10]**. In this paper, for evaluating the coexistence of Downlink-only-LAA with Downlink-only-Wi-Fi two scenarios were taken into consideration. For the **outdoor scenario**, the hot-spot scenario from 3GPPs LAA was simulated.

The buffer occupancy is defined from the LAA 3GPP document: "*When traffic is DL-only, the buffer occupancy of the i-th small cell (Wi-Fi and LAA) is defined as the sum of the period of time during which the i-th small cell has data to transmit including retransmissions (i.e., its queue is not empty) divided by the total simulation time*" [3]. Then the mean buffer occupancy is gained by averaging the buffer occupancy over all the small cells of one operator.

Table 18. Per-user data rates (Mbps) for outdoor scenario with four unlicensed 20 MHz carriers shared between two operators, LAA CCA ED threshold of -62 dBm.

	Total served traffic per operator and macro cell [Mbps]					
	35	40	60	80	100	120
Op. A Wi-Fi mean	110	100	75	43	20	NA
Op. B Wi-Fi mean	110	100	75	43	20	NA
Op. A LAA mean	165	160	148	130	120	90
Op. B Wi-Fi mean	118	115	100	85	60	40
Op. A LAA mean	170	165	158	148	140	130
Op. B LAA mean	170	165	158	148	140	130
Op. A Wi-Fi 5th perc	50	40	18	5	1	NA

Op. B Wi-Fi 5th perc	46	40	20	5	1	NA
Op. A LAA 5th perc	118	110	90	73	50	30
Op. B Wi-Fi 5th perc	60	57	40	25	15	3
Op. A LAA 5th perc	122	119	105	93	80	70
Op. B LAA 5th perc	122	120	110	96	82	70

When Wi-Fi networks coexist, they show a higher mean buffer occupancy, which indicates that Wi-Fi nodes back off to each other more frequently than with other networks, such as LAA. This is caused by the low sensing threshold that Wi-Fi nodes use towards the other Wi-Fi signals, which is -82 dBm. LAA uses a higher threshold of -62 dBm. For this reason, LAA nodes act as better neighbors by improving the frequency reuse properties of the Wi-Fi node.

Coexistence of DL-only LAA with DL+UL Wi-Fi - For this scenario an asymmetric indoor deployment was considered. In this case the Wi-Fi network has traffic both in downlink and uplink and the traffic split is 80% and 20%, respectively. downlink rate observed in the previous results.

For the Wi-Fi network with both DL and UL traffic, the overall buffer occupancy from AP-i's perspective is defined as the sum of the time period during which either the i-th small cell or at least one of its associated stations has data to transmit including retransmissions, divided by the total simulation time [10].

Table 19. Per-user UL data rates for Op. B in indoor scenario with a single shared unlicensed 20 MHz carrier, LAA CCA ED threshold of -82 dBm.

	Total served traffic per operator and macro cell [Mbps]					
	15	20	25	30	35	40
Op. B Wi-Fi DL mean	60	45	30-10-5			
Op. B Wi-Fi DL mean	65	60	53	38	30-10-0	
Op. B Wi-Fi DL mean	70	65	60	53	45	32
Op. B Wi-Fi DL perc	20	10	1			
Op. B Wi-Fi DL 5th perc	30	23	15	7		
Op. B Wi-Fi DL 5th perc	33	28	20	15	9	5

The results show that the mean buffer occupancy when LAA coexists with Wi-Fi is significantly lower. One reason for this result is that LAA improves the reuse frequency characteristics of Wi-Fi, and the other reason is that LAA is faster in serving its traffic and vacating the channel compared to Wi-Fi. Thus, this gives Wi-Fi more transmissions opportunities.

Table 20.Per-user DL data rates (Mbps) for indoor scenario with a single shared unlicensed 20 MHz carrier, LAA CCA ED threshold of -82 dBm.

	Total served traffic per operator and macro cell [Mbps]						
	15	20	23	25	30		35	40
Op. A Wi-Fi DL mean	75	63	40-15					
Op. B Wi-Fi DL mean	75	63	40	15-0				
Op. A LAA w/o licensed carrier DL mean	90	80	78	75	50	40		
Op. B Wi-Fi DL mean	85	75	72	70	50	40		
Op. A LAA DL mean	140	135	132	130	122	115		
Op. B Wi-Fi DL mean	90	88	85	80	75	65	45	

Op. A Wi-Fi DL 5th perc	50	25	10	1				
Op. B Wi-Fi DL perc	50	25	10	1				
Op. A LAA w/o licensed carrier DL 5th perc	75	70	60	50	25	15-0		
Op. B Wi-Fi DL 5th perc	60	50	47	40	20	15-0		
Op. A LAA DL 5th perc	120	115	110	100	80	75	60	40
Op. B Wi-Fi DL 5th perc	65	60	55	50	40	30	20	

For both cases with and without a licensed carrier, LAA performs better than Wi-Fi due to LTEs fast link adaptation and robust design to handle and recover from unexpected interferences via the hybrid-ARQ protocols [10].

From the results, it can be observed that when LAA coexists with Wi-Fi using the proposed coexistence mechanisms, the Wi-Fi network achieves a better performance compared to when Wi-Fi is coexisting with another Wi-Fi network.

In Table 18, the results for the **outdoor scenario with CCA ED (energy detection) threshold of -62 dBm** are presented**.** When one Wi-Fi operator is replaced by a LAA operator, the Wi-Fi throughput increases from 110 Mbps to 118 Mbps.

The **indoor scenario with CCA ED threshold of -82 dBm** results can be seen in Table 19 and Table 20. The highest LAA throughput is achieved while coexisting with Wi-Fi, and Wi-Fi performs better coexisting with LAA, than when its coexisting with another Wi-Fi network.

This paper [10] shows that fair coexistence between LAA and Wi-Fi can be achieved through the load-based LBT protocol of LAA implementing a back off deferring period. Wi-Fi under DCF, defers the transmission after a channel is idle for an extra period to avoid collision. In this work, they add a deferring period in LBT after a channel has just become free, so that the earliest time LAA can transmit is at least as large as Wi-Fi [10].

The LBT algorithm is considered also in **Janardhanan, Vaishakh, et al. [42].** This work makes these assumptions for LAA: the licensed frequency band uses 10 MHz bandwidth, while the unlicensed band uses a 20 MHz bandwidth. The transmission power for the eNodeB in the unlicensed band is 18 dBm. The CCA-ED threshold is -62 dBm, while the CCA duration is 20 micro sec.

The simulations for the coexistence evaluation were done for two scenarios, indoor and outdoor. The LAA indoor deployment scenario is based on scenario 3 from LTE Rel-12 (SCE) study, while for the LAA outdoor scenario, from scenario 2.

For each environment, three different coexistence cases are evaluated.

- Case 1- Wi-Fi coexisting with another Wi-Fi network –
- Case 2 - One of the Wi-Fi networks is replaced with LAA. Case 2
- Case 3: Both Wi-Fi networks are replaced with LAA. The performance metrics are presented for the two different LAA operators.

The performance metrics that were recorded are the UPT (User perceived throughput) and BO (Buffer Occupancy)

Table 21. UPT for cell edge user of 5% user

	Low Load	Medium Load	High Load
Wi-Fi in Case 1	3.7	1.7	0.65
Wi-Fi in Case 2	8.1	4.3	4.6
LAA in Case 2	36.1	12.7	8.1

Table 22.UPT for cell center user of 50% user

	Low Load	Medium Load	High Load
Wi-Fi in Case 1	65.7	18.4	6.09
Wi-Fi in Case 2	71.7	58.2	51.3
LAA in Case 2	81.9	47.4	49.1

Table 23.UPT for high SINR user of 95% user

	Low Load	Medium Load	High Load
Wi-Fi in Case 1	108.6	108.1	108.1
Wi-Fi in Case 2	108.5	108.5	108.1
LAA in Case 2	114.7	108.6	114.7

The results show that for all the load conditions (see Table 21, 22 & 23) the UPT of Wi-Fi is improved significantly when one Wi-Fi operator is replaced with LAA. Because LTE utilizes the spectrum in a more efficient way than Wi-Fi, it gives Wi-Fi more transmission opportunities. This is evident from the Buffer Occupancy results, that show a reduced Wi-Fi BO in the second case. For the Wi-Fi buffer occupancy results, see Table 24 below.

Table 24. Wi-Fi Buffer Occupancy

Low Load		Medium Load		High Load	
Wi-Fi & Wi-Fi	Wi-Fi & LAA	Wi-Fi & Wi-Fi	Wi-Fi & LAA	Wi-Fi & Wi-Fi	Wi-Fi & LAA
17.6	9.97	41.71	19.52	56.5	22.74

When both Wi-Fi operators are replaced by LAA operators, fairness can be achieved through the LBT scheme with back-off. Also, when LAA coexists with Wi-Fi, Wi-Fi does not suffer performance degradation, but the performance of the remaining Wi-Fi is improved for all the loads.

Next we describe the work in **3GPP Study on Licensed-Assisted Access to Unlicensed Spectrum [3].** The LAA "Study Item" focused on evaluating the coexistence between Wi-Fi and a LAA network, and LAA coexistence with another LAA network.

Results are presented for two different scenarios: indoor and outdoor. The indoor scenario is based on Scenario 2 from the proposed deployment scenarios mentioned in chapter 2, while the outdoor scenario is based on Scenario 3. These scenarios can be seen in the Figure 7 below.

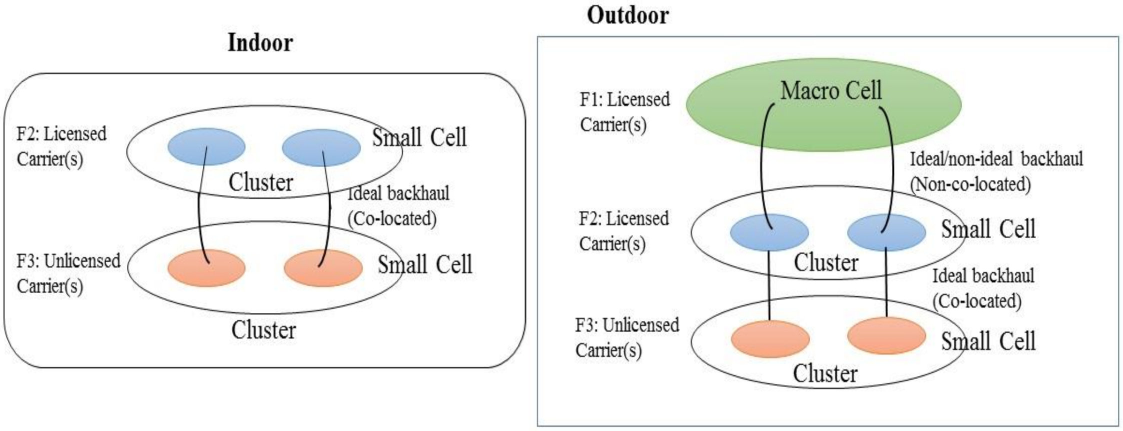

Figure 7 Evaluation Scenarios

For the simulations, the bandwidth for the unlicensed carrier is 20 MHz in the 5.0 GHz frequency band. The licensed carrier has a bandwidth of 10 MHz with the carrier at 3.5 GHz. For Wi-Fi, the IEEE 802.11ac technology is assumed.

The eNodeB transmission power for the licensed cell is 24 dBm, while for the unlicensed cell, it is 18 dBm across aggregated carriers.

For the **indoor scenario** 4 LAA eNodeBs and Wi-Fi APs are deployed by each operator in the single-floor building of size 120m x 50m.

For the **outdoor scenario**, a hexagonal grid is used with 3 sectors for each site, and the inter site distance is 500 m. The clusters of small cells are deployed randomly within the macro area. Four small cells for each operator are randomly deployed within each cluster. The traffic models that are considered are: File Transfer Protocol (FTP) traffic, mixed FTP and Voice over Internet Protocol (VoIP) traffic, and mixed FTP and Voice over Internet Protocol (VoIP) traffic.

For the Wi-Fi network, first only the downlink traffic was considered, and then both downlink and uplink traffic were considered.

For the evaluation of the coexistence first the performance of the two coexisting Wi-Fi networks is measured, then one of the Wi-Fi networks is replaced with a LAA network and the results are compared.

In the discussion at 3GPP, it was determined that due to the proximity of the LAA eNodeBs and Wi-Fi APs it is more difficult to ensure coexistence between them in the indoor environments than for the outdoor environments.

3GPP considers the user perceived throughput (UPT) an important performance measure for network serving non-full-buffer traffic [3]. The amount of data over the actual time spent for downloading (without taking into account the idle time for waiting files to arrive) is defined as the UPT.

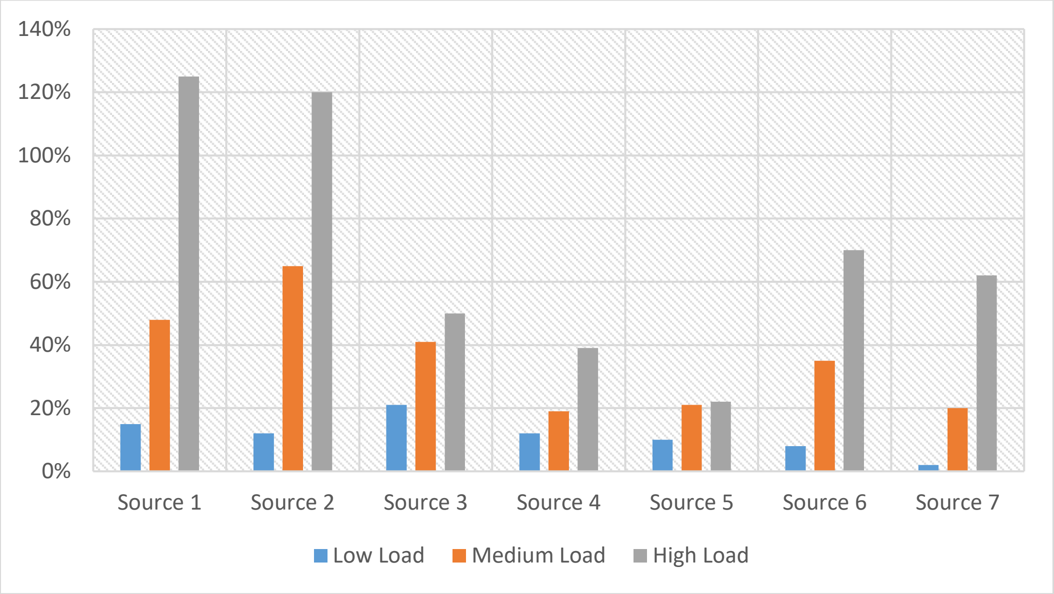

Figure 8. Improvement in UPT Performance when Wi-Fi coexists with LAA[4]

The buffer occupancy of 15-30%, 35-50% and 60-80% averaged over the access points of the non-replaced Wi-Fi network is low load, medium load and high load, respectively. From the results in Figure 8, it can be seen that the UPT of the Wi-Fi network is improved when coexisting with a LAA network. The reason is because LTE has a higher spectral efficiency compared to Wi-Fi, from the better link adaption it has based on the CSI feedback, and such messages are able to go through the licensed carrier.

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[4] Sources 1-7 are from 3GPP contributions R1-150694, R1-152732, R1-151821, R1-152863, R1-153384, R1-153426, and R1-153629, respectively

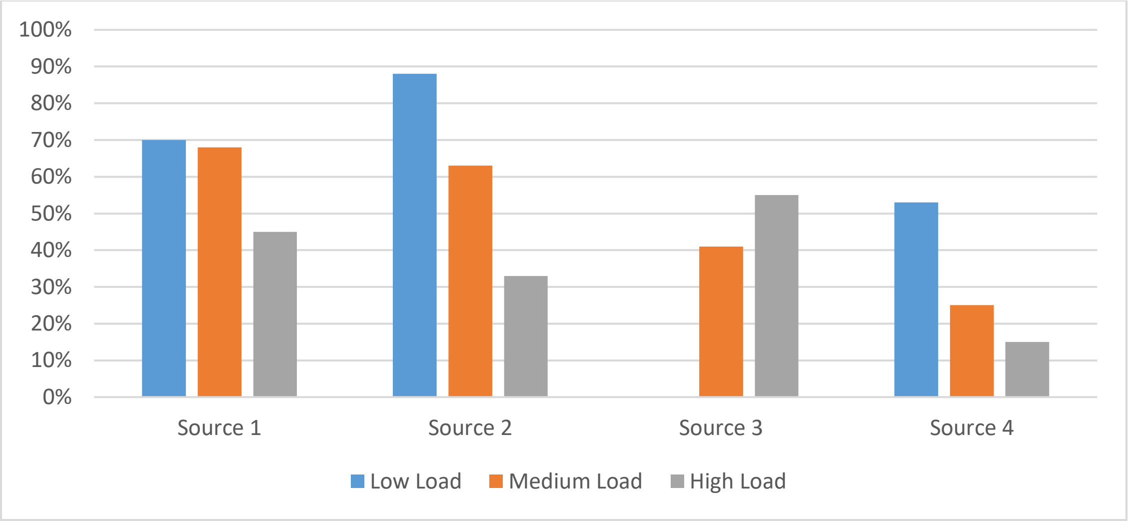

Figure 9. Decrease in VoIP Outage Percentage [5]

In Figure 9, the VoIP outage results are presented. The VoIP outage for the Wi-Fi network significantly reduces when coexisting with LAA.

The next work, **Kini, Ananth V., et al. [43]** considers two types of the LBT algorithm. For evaluating the coexistence of Wi-Fi and LAA, the two types of LBT are:

- LBT with a fixed Contention Window (CW)
- LBT with a variable CW, two different strategies for resizing the CW and two different energy detection (ED) thresholds for all LBT schemes.

First the results were presented for the case of different CW schemes: Fixed CW, Variable CW Option 1 (count based) and Variable CW Option 2 (NACK based). Before the devices

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[5] Sources 1-4 are from 3GPP LAA study contributions R1-152326, R1-152642, R1-152937, and R1-153343, respectively

transmit, they first perform the CCA check to sense the channel. If the CCA falls below a defined threshold, it performs the extended CCA (eCCA). During the eCCA, the device will observe N occupied slots before transmitting. N is a random number in [1, q], where q is the maximum contention window. In **Fixed CW**, q is a fixed value. In **Variable CW option 1** (count based), when the device enters the extended CCA, it senses the channel for q observation slots. If the device fails to find N idle slots in q observation slots, the maximum CW is doubled and it is used as the new CW. However, if the device is able to find N slots before q expires, it immediately transmits and resets q back to the default value. In **Variable CW option 2** (NACK based), resizing of CW is based on negative acknowledgements indicating that the receiving node is experiencing high interference [43].

Table 25 DL UPT(Mbps) for Wi-Fi under Wi-Fi-Wi-Fi and Wi-Fi-LAA coexistence

	DL packet arrival rate (packets/sec)										
	0.7	0.75	0.8	0.85	0.9	0.95	1	1.05	1.1	1.15	1.2
Wi-Fi Avg. UPT (Wi-Fi - Wi-Fi)	78	70	65	60	55	50	43	36	33	30	27
Wi-Fi - LAA - fixed CW	84	76	70	65	60	55	45	43	40	35	33
Wi-Fi - LAA var. CW Op.1	80	75	70	63	56	50	43	38	35	33	30
Wi-Fi - LAA var. CW Op.2	85	79	75	67	63	57	53	45	42	40	35
Wi-Fi 5%-ile UPT (Wi-Fi - Wi-Fi)	20	16	13	10	9	8	7	6	5	6	4
Wi-Fi - LAA - fixed CW	26	20	17	14	13	12	10	9	7	6	6
Wi-Fi - LAA var. CW Op.1	24	19	16	12	11	10	9	8	7	6	4
Wi-Fi - LAA var. CW Op.2	26	22	19	16	15	13	11	10	9	7	6

From Table 26 we see that LAA performs better with a variable CW, where NACK based resizing achieves the best performance. The same stands for Wi-Fi (see Table 25), where with variable CW option 2, the UPT was 85 Mbps.

Table 26. DL UPT(Mbps) for LAA under Wi-Fi-LAA coexistence for all LAA LBT options and LBT CCA-ED = -82 dBm.

	DL packet arrival rate (packets/sec)										
	0.7	0.75	0.8	0.85	0.9	0.95	1	1.05	1.1	1.15	1.2
LAA Avg. UPT (fixed CW)	179	71	64	50	41	35	29	28	25	23	20
var. CW Op.1	80	73	65	56	48	41	32	30	29	28	25
var. CW Op.2	81	75	70	60	50	45	38	32	30	29	26
LAA 5%-ile UPT (fixed CW)	15	10	9	7	6	5	3	2	1	1	0.5
var. CW Op.1	15	11	10	8	6	5	4	3	2	1	0.5
var. CW Op.2	20	12	10	9	7	6	5	4	3	2	1

The simulation was repeated for the LBT CCA-ED threshold of -62dBm. The results show that operating at a lower ED threshold significantly impacts the performance of the coexisting Wi-Fi. (See Table 27). It can be seen that by using the LBT algorithm with fixed CW and variable CW, fair coexistence between Wi-Fi and LAA can be achieved. From the three LBT CW options, the NACK based gave the best performance, while the count based CW gave the worst performance.

The highest UPT Wi-Fi achieves, is when Wi-Fi coexists with LAA implementing variable CW. The value is higher than when Wi-Fi coexists with another Wi-Fi network. Which shows that

LAA not only is a better neighbor to Wi-Fi that Wi-Fi to itself, but also improves the Wi-Fi performance.

Table 27. DL UPT(Mbps) for Wi-Fi under Wi-Fi-Wi-Fi and Wi-Fi-LAA coexistence for all LAA LBT options and LBT CCA-ED = -62 dBm.

	DL packet arrival rate (packets/sec)										
	0.7	0.75	0.8	0.85	0.9	0.95	1	1.05	1.1	1.15	1.2
Wi-Fi - Wi-Fi UPT	77	70	65	60	55	49	41	37	35	30	27
Wi-Fi - LAA (fix. CW)	68	61	52	44	37	35	27	26	22	21	20
var. CW Op.1	68	59	51	40	34	3	25	24	23	21	20
var. CW Op.2	70	65	57	50	37	35	29	25	23	21	20

In a joint effort made by Qualcomm Technologies and Deutsche Telekom AG, the world's first over-the-air LAA trial was conducted in **Qualcom[28].** We describe briefly the work based on [28].

The trial demonstrates these advantages that LAA has over Wi-Fi performance:

(i) Increased coverage, increased capacity and fair coexistence that benefits the other technologies.

(ii) When 4 Wi-Fi AP coexist, they found that the average downlink throughput is 10.8 Mbps.

(iii) When two of those Wi-Fi APs are replaced with LAA, the average downlink throughput increases to 16.3 Mbps. The Wi-Fi downlink throughput improves from approximately 12 Mbps up to 17 Mbps when coexisting with LAA. In Figure 10, a pie chart explains the channel occupancy of 4 coexisting Wi-Fi APs. We see that when 2 of the Wi-Fi AP are replaced with LAA, fair sharing of the channel is promoted.

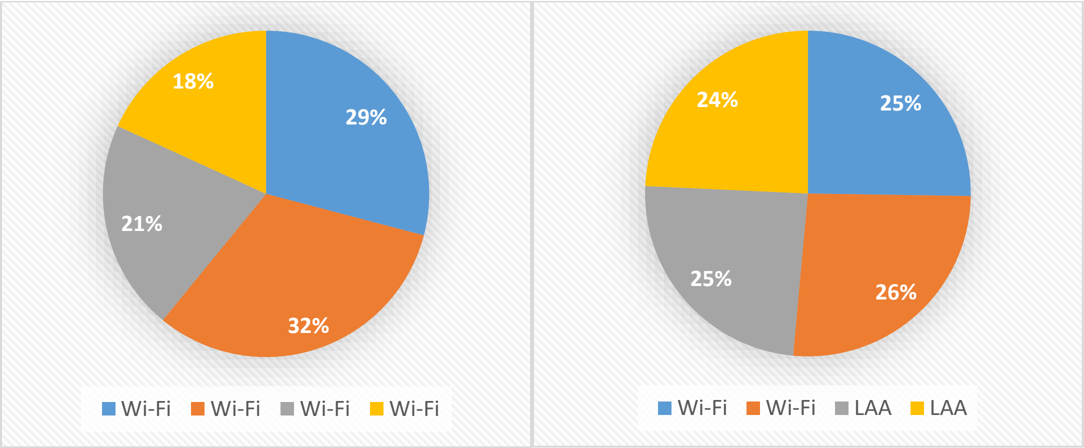

Figure 10. a. Baseline case with 4 Wi-Fi neighbors b. Replacing 2 Wi-Fi pairs with LAA[6]

In Figure 10.a. we see that the channel occupancy is not fairly shared between the four Wi-Fi networks. When two of the Wi-Fi networks are replaced with LAA (Figure 10.b), the channel occupancy between the 4 Wi-Fi APs varies only 1%.

In summary, from all the measurements the joint effort has done, by replacing a Wi-Fi AP with a LAA small-cell, for all the users, higher throughput is achieved. Through LBT, it is ensured

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[6] Due to over utilization, the total in the pie charts is not 100%

that the channel is shared fairly between the users. And they again conclude that LAA is a better neighbor to Wi-Fi than Wi-Fi itself.

Another trial on fair sharing the unlicensed band between Wi-Fi and LAA considering LBT is done in **Ericsson [44].** From Ericsson's Fair sharing trial, we see that when Wi-Fi coexists with another Wi-Fi network, the highest Object Data Rate per User that can be achieved per user in a macro cell is approximately 240 Mbps. The object data rate drops with the increase of the served traffic, as can be seen in Table 28 below.

Table 28. Object Data Rate per User (Mbps) for two Wi-Fi operators only

	Total served traffic per operator and macro cell [Mbps]				
	100	200	300	400	500
Wi-Fi A mean	240	200	150	110	
Wi-Fi B mean	240	200	135	75	
Wi-Fi A 5th percentile	175	90	45	25	NA
Wi-Fi B 5th percentile	175	100	45	25	NA

Table 29. Object Data Rate per User (Mbps) for Wi-Fi and LAA coexisting using coexistence LBT

	Total served traffic per operator and macro cell [Mbps]				
	100	200	300	400	500
LTE A ON/OFF mean	275	240	180	130	100
Wi-Fi B mean	250	230	175	125	
LTE A ON/OFF 5th percentile	210	110	60	25	
Wi-Fi B 5th percentile	175	130	60	40	30

In Table 29, it can be seen that when Wi-Fi is coexisting with LAA that implements the LBT algorithm the object data rate per user increases to 250 Mbps (slight improvement compared to Wi-Fi performance when coexisting with another Wi-Fi network). This is another study to prove that LAA is a much better neighbor to Wi-Fi than Wi-Fi is to itself.

Finally, we describe the work based on **Song, Yujae, Ki Won Sung, and Youngnam Han.[45].** To evaluate the coexistence of Wi-Fi and LBT enabled cellular networks, a mathematical model is provided in this paper. The LBT procedure that was introduced in [3GPP Rel 13, June 2015] is described as a Markov chain that is combined with *Bianchi's Markov* model to represent the operation of a Wi-Fi AP.

This paper considers the scenario where ***m*** Wi-Fi APs and ***n*** eNodeBs share the unlicensed spectrum. All the Wi-Fi and LAA nodes are supposed to coexist on the same frequency channel. The results of this scenario are compared to a scenario of ***m+n*** Wi-Fi APs only.

The numerical results present the achieved throughputs of Wi-Fi APs and the cellular eNodeBs using the LBT with random back-off and another LBT scheme, the LBT with deterministic back-off. LBT with deterministic back-off has the deterministic duration for channel sensing which equates to the CCA time plus Z times as long as the slot time [45], while LBT with random back-off performs back-off after the CCA.

From the results, presented in Table 30, it can be seen that for both the LBT schemes, the throughput of the two cellular networks is maximized for small CW sizes of the cellular BSs.

The required coexistence for the random back-off LBT is achieved for a CW size of 14 and 15, while for the deterministic back-off LBT, no CW size completes the coexistence requirement.

With the increase of the CW size, the Wi-Fi throughput is increased and the LAA throughput decreases. For a CW size of 5 for LAA, the total throughput for both Wi-Fi and LAA is 55 Mbps, while the LTE performance drops from 25Mbps to 10Mbps with the increase of CW size. The Wi-Fi throughput increases from 4 Mbps to 18 Mbps.

Table 30. Achieved throughputs (Mbps) according to the change in the CW size of cellular BS under different network scenarios and LBT schemes

	CW size of cellular BS (Z)			
	5	10	15	20
Total throughput (m=4)	55	55	55	55
Throughput per Wi-Fi AP (m=4)	15	15	15	15
Total throughput (LBT -RB, m=2, n=2)	58	58	57	57
Throughput per cellular BS (LBT-RB, m=2, n=2)	25	19	15	10
Throughput per Wi-Fi AP (LBT-RB, m=2, n=2)	4	10	15	18
Total Throughput (LBT-DB, m=2, n=2)	58	56	55	55
Throughput per cellular BS (LBT-DB, m=2, n=2)	17	5	2	1
Throughput per Wi-Fi AP (LBT-DB, m=2, n=2)	11	22	26	29

4.0 COMPARISON

The studies considered in Chapter 3 presented results for different simulations. Based on some parameters the studies are divided to compare and evaluate their results.

4.1 PLAIN CO-EXISTENCE

Table 31 presents the 5 studies that conducted simulations for the *plain* coexistence between LTE and Wi-Fi. The first two entries represent results for two different indoor deployments: Sparse and Dense done by the same study. Even though the studies used different simulation test beds, the results show similar trends.

Table 31. Throughputs [Mbps] for plain coexistence between LTE and Wi-Fi for Indoor/Outdoor deployments

	LTE Only	Wi-Fi only	LTE sharing the channel with Wi-Fi	Wi-Fi sharing the channel with LTE
Indoor Scenario				
Cavalcante, Andre M., et al. [33]	23.4	6.1	22.4	1.4
Cavalcante, Andre M., et al. [33]	32.2	8	32.2	0.27
Nihtila, Timo, et al. [36]	37	17	33	1
Jeon, Jeongho, et al. [37]	16.33	28.73	9.67	27.66
Outdoor Scenario				
Jeon, Jeongho, et al. [41]	100	138	68	38
Jeon, Jeongho, et al. [37]	27.74	10.28	21.45	1.88

For the first three studies, we see that when LTE and Wi-Fi share the same channel, the LTE performance is affected slightly, while the Wi-Fi throughput drops to as low as 3% of its standalone throughput.

Only in study [37] do we see a different trend. The Wi-Fi throughput suffers slightly, while the LTE throughput drops to half of its value. The reason behind this different trend can be that the indoor deployment used for the simulation, was a mixed indoor/outdoor deployment. The signal strength of LTE eNodeB is perhaps weaker compared to the Wi-Fi signal strength because of the penetration loss. Hence the LTE signal does not cause a high interference to the Wi-Fi APs.

For the outdoor scenario, the trend is similar, in that LTE suffers a slight performance degradation (from 27.74 to 21.45 Mbps), while Wi-Fi performance drops from (10.28 to 1.88 Mbps). In the study [41], the trend is similar although the simulation testbed differs. They measured the optical cell radius for LTE and for Wi-Fi they simulated a high signal strength AP to compete for the same channel. LTE performance is affected by dropping from 100 to 68 [Mbps] but the Wi-Fi throughput suffers a decrease of 100 Mbps.

These plain coexistence results only confirm what was known, that when sharing the same channel, LTE does not contend for the channel. LTE simply transmits and reduces the chances of Wi-Fi to get a hold of the channel since it is contention based.

4.2 COEXISTENCE WITH LTE-MUTING

Two papers considered LTE muting as a coexistence mechanism to provide Wi-Fi a fair share for channel access. These studies were conducted before LTE-U/LAA coexistence mechanisms were defined (see Table 32).

Table 32. Results for coexistence performance when LTE muting is implemented (Throughput [Mbps])

	LTE only	Wi-Fi only	LTE performance with LTE muting	Wi-Fi performance with LTE muting
Jeon, Jeongho, et al. [37] outdoor	27.74	10.28	13.87 (50%)	3.66 (36%)
Jeon, Jeongho, et al. [37] indoor/outdoor	16.33	28.73	8.71 (53%)	28.39 (99%)
Nihtila, Timo, et al. [36]	32	15	13	9

When LTE muting is implemented for outdoor deployment, we can see that LTE performance drops by half, and still the Wi-Fi throughput drops to 36% compared to baseline case. For the combined indoor/outdoor deployment, there results differ. We see that LTE throughput drops to half, while the Wi-Fi throughput suffers a slight reduction (from 28.73 to 28.39 [Mbps]). The interference from LTE was already small because of the penetration loss, and with LTE muting that remaining interference is reduced and hence the results.

In the other study [36], 60% muting of LTE was implemented, and in these conditions LTE suffers too much, while Wi-Fi does not gain enough in throughput. And since the idea of introducing LTE in the unlicensed spectrum is to optimally use the unlicensed spectrum, muting of LTE transmissions is not an optimal solution.

4.3 LAA AND CO-EXISTENCE

We summarize the work on LAA and co-existence next.

Table 33. Throughput for Wi-Fi and LAA when coexisting in Indoor/Outdoor deployments

	Wi-Fi coexists with W-Fi	Wi-Fi coexists with LAA	LAA coexists with Wi-Fi	LAA coexists with LAA
Outdoor				
Li, Yuan, Juan Zheng, and Qiang Li. [40], Fixed CCA	26	32	20	43
Li, Yuan, Juan Zheng, and Qiang Li. [40], Adapt. CCA	26	33	24	53
Mukherjee, Amitav, et al. [10]	110	118	165	170
Ericsson [44]	240	250	275	N/A
Indoor				
Li, Yuan, Juan Zheng, and Qiang Li. [40], Fixed CCA	35	40	40	50
Li, Yuan, Juan Zheng, and Qiang Li. [40], Adapt. CCA	35	40	43	58
Mukherjee, Amitav, et al. [10]	75	90	140	N/A
Both				
Janardhanan, Vaishakh, et al. [42]	65.7	71.7	81.9	N/A
Kini, Ananth V., et al. [43] fixed CW	78	84	179	N/A
Kini, Ananth V., et al. [43] variable CW	78	85	81	N/A
Song, Yujae, Ki Won Sung, and Youngnam Han.[45]	15	15	15	

In Table 33, the results of studies evaluating the Wi-Fi and LAA performance are presented. There are two entries for study [40] because the results represent two cases: The CCA threshold is adjusted adaptively or the CCA threshold is fixed. And in [43], the Contention

Window (CW) is fixed or variable. Lastly, [45] is an analytical study and its results represent the throughput for a CW size of 15.

For the outdoor scenario, the Wi-Fi throughput increases up to 10 Mbps when one of the Wi-Fi AP is replaced with an LAA network, compared to when Wi-Fi coexists with another Wi-Fi network. In comparison, for the outdoor scenario the Wi-Fi throughput improves when coexisting with LAA from 5 Mbps to 15Mbps.

In comparison of the two CCA threshold options, the adaptively adjusted CCA proves to be better, as higher throughput is achieved compared to the fixed CCA threshold. For the cases where CW is varied, the variable CW proves to have advantage over the fixed CW size.

For the studies dealing with Wi-Fi coexisting with LAA, the different speeds that are achieved come from the different simulation test beds and traffic arrival rates. Although the values are in different ranges, the trend is the same for all the studies.

The trend is maintained for both outdoor and indoor deployment, as well as for the studies that did not define the environment, and seems to demonstrate that ***LAA is a better neighbor to Wi-Fi than Wi-Fi is to itself***.

4.4 CHANNEL ACCESS PROBABILITY

Table 34 presents the results for the channel access probability. The first study [33] presents the baseline case, when Wi-Fi coexists with LTE without any coexistence mechanisms.

Table 34. Channel Access Probability

Cavalcante, Andre M., et al. [33]	Wi-Fi spends just 3.3% in transmission mode		
	LAA coexists with LAA	LAA coexists with Wi-Fi	Wi-Fi coexists with LAA
Chen, Cheng, Rapeepat Ratasuk, and Amitava Ghosh. [39] low traffic loads	50%	40%	30%
Chen, Cheng, Rapeepat Ratasuk, and Amitava Ghosh. [39] high traffic loads	50%	90%	10%
Qualcom[28]	50%	51%	49%

The results showed that the maximum time Wi-Fi spent in transmission mode is 3.3%, while the maximum time it spent in Listen mode is 99%. These percentages present the level of performance degradation Wi-Fi suffers from plain coexistence with LTE.

When LBT is implemented, we see an increase for the Wi-Fi channel access probability. In [39] the analytical results show that for low traffic loads, coexistence is achieved. But for high traffic loads, the channel access probability falls back, with Wi-Fi having a 10% chance of transmitting. In the experimental study Qualcomm [28], coexistence is achieved, where the Wi-Fi APs have a 49% chance of transmitting and LAA 51%.

5.0 CONCLUSIONS

This thesis surveys the research that has been done until now in the co-existence of LTE in unlicensed spectrum with legacy technologies like WiFi and compares the evaluations of the performance of LTE and Wi-Fi and the issues that arise when they coexist.

Studies evaluating the coexistence of LTE with Wi-Fi without using any coexistence mechanism prove that the Wi-Fi performance suffers significantly when sharing the same channel as LTE. When LTE is implemented without coexistence mechanisms, for the outdoor scenario Wi-Fi throughput drops to 18% of its original throughput, while the LTE throughput drops to 77% of its original throughput. Hence LTE outperforms Wi-Fi in almost every scenario. For the indoor scenario, the degradation of the Wi-Fi performance is caused by the LTE interference, forcing Wi-Fi to spend almost 96% of the time in Listen mode.

When LTE-U is implemented with coexistence mechanisms, the Wi-Fi throughput increases by 2-5 Mbps compared to the scenario were Wi-Fi coexists with another Wi-Fi network. LTE-U achieves slightly higher throughput rates in the outdoor scenario, approximately 5-10 Mbps which can be explained by the increase of power transmission compared to indoor environments.

In the case of LAA with the LBT algorithm, the throughput of the Wi-Fi node coexisting with LAA increases up to 10 Mbps compared to when coexisting with another Wi-Fi node. LAA itself, when coexisting with a Wi-Fi network, achieves a throughput equal or slightly higher to the Wi-Fi throughput, while when coexisting with another LAA node, its throughput increases. From the data collected and compared we can conclude that when LAA and LTE-U are implemented with coexistence mechanisms they are better neighbors to Wi-Fi than Wi-Fi itself. The deployment of LTE in the unlicensed spectrum, will increase its participation in the market share and the Wi-Fi operators will be directly affected by it. That is why many studies focused on setting strict regulatory requirements for LAA, and still focus on how LTE degrades the Wi-Fi performance, by not sensing the medium before transmitting.

Based on the studies in papers after the LBT algorithm is implemented, the Wi-Fi performance does not suffer more than what it would from other Wi-Fi networks and it is a clear indication that LAA will be a major contender for the unlicensed band.

5.1 SUGGESTIONS FOR FUTURE STUDIES

The comparison of the studies done to evaluate the performance of Wi-Fi and LTE while coexisting came with its challenges.

The factors that made It challenging were the different testbeds used for the simulations/ experiments. Each study used different simulation platforms, different traffic models, different numbers of eNB/APs, different cell sizes, different distributions of users, etc.

These differences in the studies made the comparison difficult and for future work it is important to create a standardized testbed and use the same scenarios to provide a more precise evaluation of LTE and Wi-Fi performance that are coexisting with each other.

From the studies taken into consideration for this work, only one study [38], simulated a scenario with multiple operators sharing multiple 20 MHz channels. And even that paper only presented results for the System Throughput when LAA is implemented. Hence, the case when multiple LAA operators share the same 20 MHz channel lacks data about Wi-Fi behavior.

It would be interesting to see the chance Wi-Fi has in accessing the channel when two different LAA operators are competing for the same channel. It is already stated that when two different operators coexist in the same channel, the user device will not be able to connect to the strongest cell if it belongs to another operator.

On the other side, the number of papers considering LTE-U is low. One study was analytical and the other was the report from the LTE-U forum. The lack of studies dealing with LTE-U since LAA was defined, made it harder to compare the performance between these two alternatives of LTE in the unlicensed band. For now, it is not possible to draw a conclusion as to which of these alternatives performs better. The countries that do not have regulatory requirements to implement LBT, will have to choose between these options, since the rest are required to Listen-Before-Talking.

6.0 BIBLIOGRAPHY

[1] The 1000x Mobile Data Challenge More Small Cells, More Spectrum, Higher Efficiency

[2] Overview of 3GPP Release 8, 3GPP

[3] 3rd Generation Partnership Project; Technical Specification Group Radio Access Network;Study on Licensed-Assisted Access to Unlicensed Spectrum;(Release 13)

[4] Progress on LAA and its relationship to LTE-U and MultiFireTM, Qualcomm Technologies, Inc. February 22, 2016

[5] Yubing Jian, Chao-Fang Shih, Bhuvana Krishnaswamy and Raghupathy Sivaku-mar, "Coexistence of WiFi and LAA-LTE: Experimental Evaluation, Analysis and Insights," IEEE International Conference on Communications Workshop CCW), June 2015

[6] Google Inc., "LTE and WiFi in Unlicensed Spectrum: A Coexistence Study," White paper, June 2015

[7] Cristina Cano, Douglas J. Leith, "Coexistence of WiFi and LTE in Unlicensed Bands: A Proportional Fair Allocation Scheme," IEEE International Conference on Communications Workshop (ICCW), June 2015

[8] Z. Ning, M. Saisai, X. Jing, Z. Bin, and Z. Wei, "Unlicensed Spectrum Us-age Method for Cellular Communication Systems," International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM), 2012

[9] S. Dimatteo, H. Pan, B. Han and V.O.K. Li, "Cellular traffic offloading through WiFi networks," in IEEE 8th International Conference on Mobile Ad Hoc and Sensor Systems (MASS), pp.192-201, Oct. 2011.

[10] A. Mukherjee etc., "System architecture and coexistence evaluation of licensed assisted access. LTE with IEEE 802.11," IEEE International Conference on Communications Workshop (ICCW), June 2015

[11] R. Ratasuk, M.A. Uusitalo, N. Mangalvedhe, A. Sorri, S. Iraji, C. Wijting, and A.Ghosh, "License-exempt LTE deployment in heterogeneous network," in Wireless Communication Systems (ISWCS), 2012 International Symposium on, Aug 2012, pp. 246250.

[12] Jeongho Jeon, Huaning Niu, Qian Liy, Apostolos Papathanassiou and Geng Wu, "LTE with Listen-Before-Talk in Unlicensed Spectrum," IEEE International Conference on Communications Workshop (ICCW), June 2015

[13] O. Sallent, J. Prez-Romero, R. Ferrs and R. Agust, "Learning-based Coexistence for LTE Operation in Unlicensed Bands," IEEE International Conference on Communications Workshop (ICCW), June 2015

[14] Baoan Jia and Meixia Tao, "A Channel Sensing Based Design for LTE in Unlicensed Bands," IEEE International Conference on Communications Workshop (ICCW), June 2015

[15] "LTE in Unlicensed Spectrum: Harmonious Coexistence with WiFi," https://www.qualcomm.com/media/documents/files/lte-unlicensed-coexistence-whitepaper.pdf. Retrieved November 5, 2015.

[16] Abinader, F.M., et al., "Enabling the coexistence of LTE and WiFi in unlicensed bands," IEEE Communications Magazine, 2014, Vol. 52, pp. 54-61.

[17] Rafael C. D. Paiva, Panayiotis Papadimitriou and Sayantan Choudhury, "A Physical Layer Framework for Interference Analysis of LTE and WiFi Operating in the same Band," Signals, Systems and Computers, 2013, pp. 1204-1209.

[18] Fabiano S. Chaves, et al., "LTE UL Power Control for the Improvement of LTE/WiFi Coexistence," IEEE Vehicular Technology Conference, 2013, pp. 1-6.

[19] Texas Instruments, “LTE Operation in Unlicensed Spectrum,” 3GPP RAN1 standard contribution - RWS-140012, Sophia Antipolis, France, Jun. 2014.

[20] “Review of Regulatory Requirements for Unlicensed Spectrum,” 3GPP RP-140054, Fukuoka, Japan, Sep. 2014.

[21] Extending the benefits of LTE Advanced to Unlicensed Spectrum,” Apr. 2014.

[22] HiSilicon, “Scenarios, spectrum considerations and preliminary assessment results of U-LTE,” 3GPP RAN1 standard contribution - RWS-140026, Sophia Antipolis, France, Jun. 2014.

[23] InterDigital, “A Look at the Requirements for LTE in the Unlicensed Spectrum,” 3GPP RAN1 standard contribution - RWS-140006, Sophia Antipolis, France, Jun.2014.

[24] Alcatel Lucent, “On the Standardisation of LTE in Unlicensed Spectrum,” 3GPP RAN1 standard contribution - RWS-140014, Sophia Antipolis, France, Jun. 2014.

[25] Samsung, “Performance Evaluation of LTE in Unlicensed Spectrum,” 3GPP RAN1 standard contribution - RWS-140016, Sophia Antipolis, France, Jun. 2014.

[26] ZTE, “Discussion on LTE in Unlicensed Spectrum,” 3GPP RAN1 standard contribution RWS-140021, Sophia Antipolis, France, Jun. 2014.

[27] NOKIA, “Nokia LTE for Unlicensed Spectrum,” 2014, White Paper.

[28] Qualcomm, “Extending LTE Advanced to unlicensed spectrum,” Dec. 2013, White Paper.

[30] “LTE in Unlicensed Spectrum : Harmonious Coexistence with WiFi,” Jun.

[31] Intel, “LTE Sysyem Deployment and Performance in Unlicensed Bands,” Tech Talk at IEEE ComSoc Event on LTE-U, Nov. 2014.

[32] MFA TR MF.101 V1.0.0 (2016-11)

[33] Cavalcante, A. M., Almeida, E., Vieira, R. D., Choudhury, S., Tuomaala, E., Doppler, K., ... & Abinader, F. (2013, June). Performance evaluation of LTE and Wi-Fi coexistence in unlicensed bands. In Vehicular Technology Conference (VTC Spring), 2013 IEEE 77th (pp. 1-6). IEEE.

[34] Babaei, A., Andreoli-Fang, J., Pang, Y., & Hamzeh, B. (2014). On the impact of LTE-U on Wi-Fi performance. International Journal of Wireless Information Networks, 22(4), 336-344.

[35] LTE-U Forum Report

[36] Nihtila, T., Tykhomyrov, V., Alanen, O., Uusitalo, M. A., Sorri, A., Moisio, M., ... & Mangalvedhe, N. (2013, April). System performance of LTE and IEEE 802.11 coexisting on a shared frequency band. In 2013 IEEE Wireless Communications and Networking Conference (WCNC).

[37] Jeon, J., Niu, H., Li, Q. C., Papathanassiou, A., & Wu, G. (2014, December). LTE in the unlicensed spectrum: Evaluating coexistence mechanisms. In 2014 IEEE Globecom Workshops (GC Wkshps) (pp. 740-745). IEEE.

[38] Ratasuk, R., Mangalvedhe, N., & Ghosh, A. (2014, December). LTE in unlicensed spectrum using licensed-assisted access. In 2014 IEEE Globecom Workshops (GC Wkshps) (pp. 746-751). IEEE.

[39] Chen, C., Ratasuk, R., & Ghosh, A. (2015, May). Downlink performance analysis of LTE and WiFi coexistence in unlicensed bands with a simple listen-before-talk scheme. In 2015 IEEE 81st Vehicular Technology Conference (VTC Spring) (pp. 1-5). IEEE.

[40] Li, Y., Zheng, J., & Li, Q. (2015, August). Enhanced listen-before-talk scheme for frequency reuse of licensed-assisted access using LTE. In Personal, Indoor, and Mobile Radio Communications (PIMRC), 2015 IEEE 26th Annual International Symposium on (pp. 1918-1923). IEEE.

[41] Jeon, J., Li, Q. C., Niu, H., Papathanassiou, A., & Wu, G. (2014, December). LTE in the unlicensed spectrum: A novel coexistence analysis with WLAN systems. In 2014 IEEE Global Communications Conference (pp. 3459-3464). IEEE.

[42] Janardhanan, V., Muhammed, N., Gonuguntla, V., & Akhtar, N. (2015, December). LTE-Wi-Fi coexistence in 5 GHz band. In 2015 IEEE International Conference on Advanced Networks and Telecommuncations Systems (ANTS) (pp. 1-6). IEEE.

[43] Kini, Ananth V., et al. "Wi-Fi-LAA coexistence: Design and evaluation of Listen Before Talk for LAA." 2016 Annual Conference on Information Science and Systems (CISS). IEEE, 2016.

[44] Ericsson Licensed Assisted LAA, January 2015

[45] Song, Yujae, Ki Won Sung, and Youngnam Han. "Coexistence of Wi-Fi and cellular with Listen-Before-Talk in unlicensed spectrum." IEEE Communications Letters 20.1 (2016): 161-164.

[46] Dynamic Frequency Selection (DFS) in 5GHz Unlicensed Bands. An Overview of Worldwide Regulatory Requirements. NTS

[47] ETSI TR 136 932 V12.1.0 (2014-10)

[48] LTE Aggregation & Unlicensed Spectrum. 4G Americas, November 2015