Coexistence Mechanisms for LTE and Wi-Fi Networks over Unlicensed Frequency Bands

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***Abstract*—Recently, mobile data traffic has rapidly grown which results in many challenges especially in the radio spectrum needs. Thus, operating Long Term Evolution (LTE) in unlicensed bands is becoming an attractive area of research. In particular, the idea is to utulise the unlicensed spectrum by deploying other technologies over these unlicensed bands to coexist with Wi-Fi, radar, and Bluetooth. On the other hand, this coexistence between LTE and Wi-Fi technologies faces many limitations and challenges over these bands. In this context, this paper presents a coexistence analysis between LTE and Wi-Fi over the unlicensed 5 GHz band. The coexistence mechanism is studied by deploying different scenarios of LTE. The first scenario is by using LTE-Unlicensed duty-cycling (LTE-U), while the second one is by using LTE Licensed-Assisted Access (LTE-LAA). In particular, simulation results using NS-3 simulator for the throughput and latency for different coexistence deployments are provided. The simulation results show that the coexistence mechanism between LTE-LAA and Wi-Fi in the 5 GHz band outperforms that of LTE-U with Wi-Fi. Furthermore, the results show that the design of the Listen Before Talk (LBT) algorithm in LTE-LAA plays an important role in the coexistence mechanism. On the other hand, the impact of changing some parameters on LTE and Wi-Fi performances are studied. In particular, the results show that the performance is not affected by changing many parameters of LTE and Wi-Fi and LBT algorithm needs some modifications to deploy a fair coexistence mechanism.**

***Index Terms*—Coexistence mechanism; duty-cycling; Licensed-Assisted Access; radio spectrum; 5 GHz band.**

I. Introduction

With the evolution of wireless applications and services, the spectrum shortage has become a challenging problem. Unfortunately, the cost and the availability of the licensed spectrum is also a challenging problem [1]. Therefore, it is necessary to find a solution to have more spectrum bands. One of these solutions is to utilise the unlicensed spectrum more efficiently by occupying these bands with other wireless technologies. The unlicensed bands are occupied by some wireless technologies such as Wi-Fi. These bands are attractive since they are free and there are about 500 MHz of free spectrum for different services at the 5 GHz band [2].

Recently, the unlicensed spectrum has attracted the researchers due to the large amount of accessible spectrum. On the other hand, this large spectrum is shared by other technologies such as Wi-Fi networks. Thus, it is important not to degrade the performance of these existing technologies by designing a fair coexistence mechanism. LTE technology has been recently developed to operate in unlicensed bands to give higher throughput, better performance in dense deployment, and more capacity [3]. On the other hand, the coexistence of LTE with Wi-Fi in these free bands creates many challenges since there is a main difference between the LTE and Wi-Fi MAC layers.

In Wi-Fi, the MAC layer is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism. Thus, the node senses the channel and if it is free then the transmission will take place, otherwise the node would select a random back-off timer and the transmission starts when the timer decreases to zero. While in LTE, there is no sensing scheme. As a result, the coexistence of LTE with Wi-Fi in the unlicensed bands can severely degrade the performance of Wi-Fi since the Wi-Fi node sends its own data after checking the availability of the channel. Therefore, when there is interference from LTE network which does not use any sensing scheme, Wi-Fi node stays on listen mode without any transmission. This may cause Wi-Fi starvation while LTE is slightly impacted [4].

Obviously, the idea to coexist LTE with Wi-Fi in the unlicensed band is not to unseat the Wi-Fi technology, but to increase the spectral efficiency and the capacity. The most suitable way to occupy LTE in the unlicensed spectrum is by using Licensed-Assisted Access (LAA). LAA aggregates two components carriers, the primary carrier in the licensed band and the secondary carrier in the unlicensed band which operates in an opportunistic manner [5]. The main goals of LTE-LAA system are to give a fair coexistence mechanism with the existing Wi-Fi networks in the unlicensed spectrum such that the LTE network should not degrade the throughput performance of Wi-Fi nodes and to give a fair coexistence mechanism with other LTE-LAA networks deployed by different operators such that a comparable throughput performance can be achieved [1].

The main objective of this study is to perform an exhaustive comparison analysis between LTE-U and LTE-LAA when they are deployed with Wi-Fi over the 5 GHz band. In particular, fair coexistence mechanisms of LTE and Wi-Fi technologies in the unlicensed 5 GHz band have been discussed to achieve the best performance for both technologies. Firstly, we will study the coexistence at the network level for the LTE-U and Wi-Fi networks assuming no coordination between these networks. Then, we will discuss the coexistence between LTE-LAA and Wi-Fi networks by using Category 4 Listen Before Talk (LBT) algorithm. Then, we will discuss the effects of changing some important parameters on the LTE and Wi-Fi performances taking into account the coexistence scenario.

II. Background

Based on the different advantages of deploying LTE in unlicensed spectrum such as high spectral efficiency and good performance of LTE in dense deployment, different contributions in the literature proposed different mechanisms to share the unlicensed spectrum by LTE and Wi-Fi networks in a fair manner [6], [7]. For example, the coexistence of LTE and Wi-Fi has been studied in the TV white space band in [8], the results show that LTE impacts Wi-Fi when the nodes are randomly deployed. While in [9], the authors proved that it is unfair to share the same channel between Wi-Fi and LTE nodes without a controlled procedure.

LTE technology has a centralized architecture in which a base station schedules channel access in licensed bands [10]. In contrast, Wi-Fi technology has a decentralized channel access mechanism based on a CSMA protocol [11]. Therefore, there is a need to manage this channel access differences between LTE and Wi-Fi through a fair and friendly mechanism. The regulatory requirements such as the allowed transmit power should be taken into account while designing a fair coexistence mechanism in the unlicensed spectrum. In some regions, such as Europe, an LBT protocol for Clear Channel Assessment (CCA) while accessing the unlicensed channel is required. In other regions, such as USA, there is no need for LBT protocol [12]. The first version of LTE in the unlicensed band is called LTE-U which does not use LBT mechanism, while LTE-LAA is the most recent version.

A. LTE-U and Wi-Fi Coexistence in the 5 GHz band

In some countries, such as USA, Korea and China, there is no regulation that needs LBT for the transmission over the unlicensed bands. In these countries, the design of coexistence mechanisms does not need modifying Release 10/11 LTE PHY/MAC standards, which means no modifications for the LTE interface. In such mechanisms, intelligent software is used to deploy the LTE networks with the Wi-Fi networks over the unlicensed spectrum [12].

The industry consortium LTE-U Forum is focused on coexistence mechanisms without LBT requirement. Three mechanisms can be used to deploy LTE as a good neighbour with Wi-Fi in the unlicensed spectrum without LBT. First, the Channel Selection (CHS) mechanism. Here, the LTE-U small cells monitor the channel to choose the best channel for the Supplemental Downlink (SDL) transmission, if a clean channel is identified, the Secondary Cell (SCell) can be operated without concerning of co-channel communications [13], [14]. However if there is no clean channel which can be measured by energy detection, the Carrier Sensing Adaptive Transmission (CSAT) algorithm is used [15]. The CHS is suitable where the density of traffic is low since there are clean channels.

In the CSAT algorithm, LTE-U can share the same channel with Wi-Fi or another LTE-U by using the concept of Time Division Multiplexing (TDM) coexistence based on medium sensing. In particular, the small cells sense the channel for longer duration than that duration of Wi-Fi (for LBT and CSMA), then based on the activities, CSAT defines the duty cycle of the transmission. Thus, LTE-U is periodically activated and deactivated by control elements of LTE MAC, and the Wi-Fi transmissions can be done during the OFF periods of LTE-U. The main idea of CSAT is to define the duty cycle for the transmission of LTE-U, where the SCell can transmit at a relatively high power during the CSAT ON periods, while in the CSAT OFF periods the SCell will gate off to avoid competing with Wi-Fi.

The third algorithm to deploy LTE with Wi-Fi in the unlicensed spectrum without LBT is the Opportunistic SDL (OSDL), where the secondary component in the unlicensed band can be turned off to avoid transmissions of overheads such as Cell-specific Reference Signals (CRSs) when the small cell is lightly loaded, which reduces the interference to the neighbouring Wi-Fi access points. This algorithm is suitable in areas where dense deployments, where no clean channel is available since it reduces the impact on co-channel communications [15].

The adjustment of the CSAT parameters such as the cyclic ON/OFF ratio and the transmission power depends on the measurements performed by the devices or small Base Stations (BSs). These parameters can be optimized to give better performance. In [4], a dynamic duty cycle selection technique has been introduced to give the Wi-Fi nodes more opportunities to access the channel in the unlicensed spectrum. A blank sub-frame allocation approach has been used, where some sub-frames are allocated for Wi-Fi transmissions which improves the performance of Wi-Fi and degrades the LTE performance since it is a trade-off between these technologies. In general, the coexistence between LTE-U and Wi-Fi without LBT functionality is called LTE-U duty-cycling, i.e. managing the transmission of LTE-U by ON/OFF periods. The LTE-U duty-cycling has main advantages such as it does not require big changes in the LTE specification and it is attractive where there are free available channels to increase the capacity in a short term with a fair coexistence with Wi-Fi networks. On the other hand, LTE-U duty-cycling has some drawbacks such as the controlling of the duty cycle is done by the LTE-U device. Thus, the Wi-Fi devices have to adapt to this cycle set by LTE-U which may degrade the performance of Wi-Fi network [16], [17].

B. LTE-LAA and Wi-Fi Coexistence in the 5 GHz band

In some countries, such as Europe and Japan, the LBT function is mandatory for the transmission over the unlicensed bands. LTE-LAA is the version of LTE in the unlicensed spectrum which was proposed in the 3rd Generation Partnership Project (3GPP) Release 13. The main feature of LTE-LAA is that it uses the LBT mechanism before transmission, which needs some modifications to the LTE air interface. Moreover, LAA uses the Carrier Aggregation (CA) concept which aggregates carriers from licensed and unlicensed bands. In particular, CA aggregates the Primary Cell (PCell) on licensed carrier and the Secondary Cell (SCell) on unlicensed carrier [12].

CA is one of the most important technologies in LTE advanced, where it increases the data rate, capacity, and user throughput. LAA can be used as an SDL data channel (i.e. downlink only) by using Frequency Division Duplex (FDD) or as a Time Division Duplex (TDD) data channel (i.e. downlink and uplink). The concept of LAA is that the primary carrier is always ON while the secondary carrier could be ON or OFF depending on channel availability. Thus, the control signalling and some data will be carried through the primary, while certain level of data will be carried through the secondary [1], [18].

The MAC layer of Wi-Fi technology is based on the CSMA/CA mechanism. Thus, the Wi-Fi device has to sense the channel before sending any data to avoid the collision, then the device can send the data if the channel is idle. Otherwise, the Wi-Fi device is permitted to transmit and the detection is performed using a control response (ACK) frame. On the other hand, in the licensed LTE, no such frame exists to detect the collision and there is no LBT mechanism [6]. As mentioned before, there is a major difference between the MAC layers of Wi-Fi and LTE, which yields some challenges in the coexistence of these two technologies in the unlicensed spectrum. The main challenge is that if LTE coexists with Wi-Fi on the same unlicensed band without any fair mechanism, then the performance of Wi-Fi will be affected by LTE transmission, because of the continuous nature of LTE transmission which prevents the Wi-Fi transmission. On the other hand, Wi-Fi is designated to coexist with other networks by random backoff and channel sensing mechanism [6].

In [19], two LBT algorithms have been proposed. One of them is asynchronous LBT based on the Distributed Coordination Function (DCF) protocol since it uses the RTS/CTS signals to check the availability of the channel. The other one is synchronous LBT, where the data subframes are synchronized with the licensed LTE carrier. Thus, the second algorithm needs some changes in the LTE specification.

In these markets where the LTE transmission follows an LBT algorithm in the unlicensed spectrum, a periodic check to sense the channel (listen) before transmitting (talk) is required. Thus, when a device or a BS needs to transmit, it has to detect the energy level at a certain time equal to the Clear Channel Assessment (CCA) period. The LBT procedure is a major feature for fair coexistence between LAA and Wi-Fi in the unlicensed spectrum as stated in the 3GPP TR 36.889, it also uses Energy Detection (ED) to determine the availability of the channel [20], [21].

3GPP TR36.889 defines the meaning of fair coexistence between LTE and Wi-Fi in the 5 GHz as "*the capability of an LAA network not to impact Wi-Fi networks active on a carrier more than an additional Wi-Fi network operating on the same carrier, in terms of throughput and latency*" [1], [5].
As a result, the design of LAA should take into account many things such as fair and effective coexistence mechanism with Wi-Fi, and the design should achieve a comparable performance between different LAA deployed by different operators in terms of throughput and latency.

1) Listen Before Talk (LBT) in LTE-LAA: Different results in the literature show that there is a severe impact on Wi-Fi network performance by deploying LTE with the Wi-Fi in the unlicensed spectrum without LBT capabilities, and this impact is greater than the impact of deploying another Wi-Fi network. Moreover, many studies show that the use of LBT is necessary for a fair coexistence between LTE and Wi-Fi in the 5 GHz band, but also the parameters and the design of this LBT algorithm play an important role in this fairness [5], [22].

Thus, LBT uses a CCA period which is considered the listening time of the channel to check the channel availability. Moreover, an energy detection threshold is specified by the regulatory requirements in the regions where LBT is mandatory for transmission over unlicensed spectrum [12]. Then, any node receives energy above this threshold, the node assumes the channel is not available. This threshold can be changed adaptively in LAA especially for the DL. However, there is a difference in the design of LBT for LAA DL and LAA UL since the LAA UL is based on scheduled access which affects the User Equipment's (UEs) channel contention opportunities [6].

3GPP designs different kinds of channel access schemes. Firstly, LBT without backoff, where the time duration of sensing the channel to be idle is deterministic. Secondly, LBT with a fixed contention window, where the transmission follows a fixed contention window by generating a random number N within a fixed contention window size. This random number N is used in the LBT algorithm to determine the sensing time duration. Thirdly, LBT with a variable contention window, where LBT uses a variable size for the contention window instead of the fixed one to determine the duration of sensing the channel to be idle before transmitting [17]. As a result, the eventual algorithm selected by the 3GPP TR 36.889 was that one which is considered similar to how Wi-Fi networks implement LBT and it is called Category 4 LBT. Many modifications should be done to the PHY/MAC LTE to meet the LBT algorithm such as discovery signals to discover and acquire access, LBT using CCA for regional requirements, beacon signals for channel reservation for transmission and Hybrid Automatic Repeat Request (HARQ) protocol.

2) Category 4 LBT in LTE-LAA: In Wi-Fi, a DCF is used to resolve the channel contention among different nodes by using a random backoff counter. Thus, any node should sense the channel and observe a clear channel for a deferral period, then if the channel is clear, the node can transmit immediately. Otherwise, if the medium is sensed to be already occupied, the transmission is deferred and an Extended CCA (ECCA) is performed until the channel is deemed to be idle.

In the ECCA check, the operating channel is observed for a time equal to a random number N multiplied by the CCA slot time, where N defines the number of idle slots that need to be observed before initiation of the transmission. The value of N is randomly selected as N in the interval [1, q], where every time an extended CCA is required and the value of q is the upper bound of the contention window, which varies according to an exponential backoff. The counter is decremented every time a CCA slot is deemed to be unoccupied, when the counter reaches zero, the node may transmit. Moreover, the collision detection is performed using an ACK frame [18]. However, there is a similarity between LBT algorithm in Wi-Fi and LBT algorithm in LAA.

III. METHODOLOGY

The methods developed in this work will be evaluated by means of simulations conducted with the NS-3 simulator. This simulator is open-source simulator which allows researches to share their contributions. It is a new version network simulator and it is not a compatible extension of NS-2 simulator. Thus, the NS-3 does not support the NS-2 applications [23].

One of the NetDevices in NS-3 is WifiNetDevice which creates models of 802.11-based infrastructure. NS-3 provides models for different aspects of 802.11 (both 2.4 GHz and 5

GHz bands) [24]. It has different propagation loss models, propagation delay models and control algorithms. Moreover, WifiNetDevice in NS-3 can coexist with other NetDevices, which is unimplemented in NS-2.

The NS-3 LTE module was developed by the LENA project to design and evaluate the performance of many issues in LTE systems such as DL and UL MAC schedulers, radio resource management algorithms, cognitive LTE systems, etc [25].

The methodology for evaluating the fairness mechanism follows the 3GPP TR36.889. In particular, Category 4 LBT for LAA has been implemented. Two operators have been considered using the same channel in the 5 GHz band. The performance has been evaluated in three steps. In step 1, both operators deploy Wi-Fi technology. In step 2, one operator deploys LTE-U (Duty-Cycling without LBT) technology and the other operator deploys Wi-Fi technology. In step 3, one operator deploys LTE-LAA (Category 4 LBT) technology and the other operator deploys Wi-Fi technology.

We are interested in the indoor scenario and the layout is depicted in Fig. 1 with 20 User Equipments (UEs)/Stations (STAs) for each operator randomly distributed in a rectangular area and 4 Base Stations (BSs)/Access Points (APs) for each operator. The FTP Model 1 has been implemented here considering the downlink scenario for a file of 0.5 Mbytes size transfers arriving based on a Poisson process with arrival rate of 1.5. The details of the simulation scenario are compared with the 3GPP model in Table 1. 802.11n 2x2 MIMO for Wi-Fi system is considered, and there is a tunable Energy Detection (ED) threshold to detect other radio access technologies (RATs). The default ED threshold is -62 dBm, while Preamble Detection (PD)-based for Wi-Fi allows for frame detection at the threshold of signal detection around -82 dBm. This means that Wi-Fi will defer to weaker Wi-Fi signals sensed on the channel compared to LTE signals which is at -62 dBm threshold. On the other hand, the LAA ED threshold is tunable separately from ED threshold of Wi-Fi and it is defaulted to -72 dBm. The parameter (TxOP) which describes the maximum length of transmission is set to 8 msec and it is configurable. The Contention Window Size (CWS) follows the rule of a HARQ feedback where the HARQ declares a collision and then the CWS is updated if Z=80% of feedbacks from the first subframe of the latest transmission burst are NACKs. Otherwise, the CWS is reset to 15 since the upper bound of the contention window varies between {15, 31, 63} based on Category 4 LBT. As mentioned before, based on 3GPP TR 36.889, the main performance metrics in the coexistence mechanisms are the throughput and latency. As the results will show, different loads have been simulated by changing different parameters to study the effects of changing these parameters on the coexistence performance.

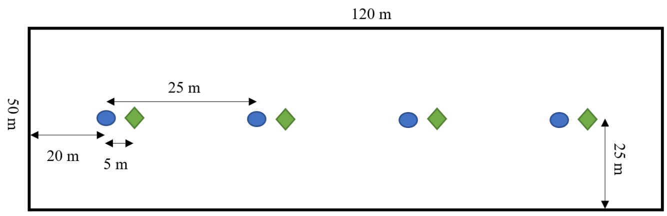

Fig. 1. 3GPP indoor topology.

TABLE I
3GPP TR 36.889 VERSUS NS-3.

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

IV. Simulation Results

The amount of data received on a flow divided by the time interval between the first and last packet of the flow as observed at the IP layer is defined as the throughput. While the latency is an expression of how much time it takes for a packet of data to get from one point to another. As illustrated in Fig. 2, the plots are Cumulative Distribution Functions (CDFs) of file transfer throughputs and latencies observed during the simulation for different deployments; Case A: Wi-Fi with Wi-Fi, Case B: LTE-U with Wi-Fi and Case C: LTE-LAA with Wi-Fi. It can be seen that when only two Wi-Fi networks coexist, they achieve similar performance. An ideal LTE coexistence mechanism should allow the Wi-Fi network to achieve the same performance shown in Fig. 2a. Therefore, this result can be used as a reference to evaluate new proposed LTE mechanisms. In particular, the more effective (fair) LTE mechanism is in Case C, i.e. the closer Wi-Fi performance to the results shown in Fig. 2a, where the deployment is LTE-LAA with Wi-Fi since there is a controlled coexistence based on Category 4 LBT. While in Case B there is a degradation in the Wi-Fi performance due to the uncontrolled mechanism of LTE-U. Moreover, in Case C, LTE-LAA latency averages between (17-28) ms, with a few outlier values that range up to 118 ms. Wi-Fi latencies are similar with a maximum latency of 50 ms. Based on the obtained results, it can be concluded that LTE-LAA provides a more fair coexistence between LTE and Wi-Fi than LTE-U.

Different CDFs of throughputs and latencies are depicted in Fig. 3 for Case B deployment (LTE-U and Wi-Fi) with different duty cycles to study the effect of this parameter on the coexistence performance. It can be noted that the performance of LTE improves as the LTE duty cycle increases because this allows LTE to transmit more often, however there is a degradation in the performance of Wi-Fi as well. On the other hand, a fair coexistence can be seen when the duty cycle is set to 0.2. Basically, Fig. 3 shows that with LTE-U, the only way to provide a fair coexistence is by keeping the DC very low (e.g. DC=0.2), however in this case the LTE performance is degraded (i.e., low throughput and high latency) and the access to the unlicensed band may not provide the sought increased capacity and performance for LTE.

Fig. 4 depicts the CDFs of throughputs and latencies for

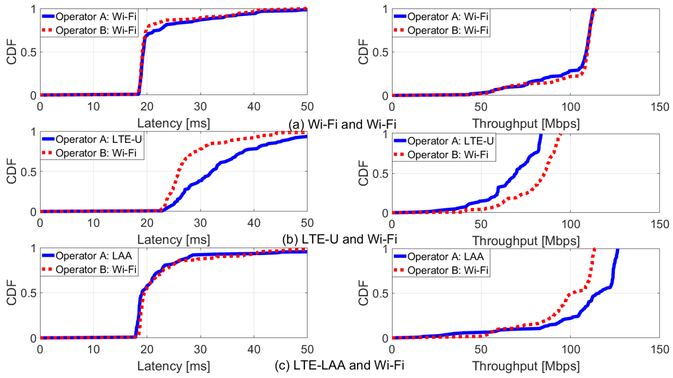

Fig. 2. Throughputs and latencies for different coexistence deployments: (a) Wi-Fi and Wi-Fi, (b) LTE-U and Wi-Fi, (c) LTE-LAA and Wi-Fi.

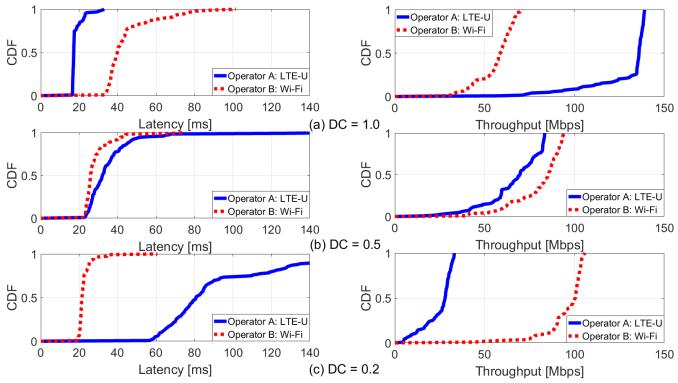

Fig. 3. Throughputs and latencies for several DC values of LTE-U: (a) DC = 1.0, (b) DC = 0.5, (c) DC = 0.2.

Transmission Control Protocol (TCP) and User Datagram Protocol (UDP). Firstly, low throughput is noticed for LTE-LAA and Wi-Fi TCP case compared with the Wi-Fi and Wi-Fi TCP case due to the typical protocol stack delays in LTE; the delay can be high because of the need to send buffer status reports, receive an uplink DCI message on the DL, and scheduling the ACK for transmission on a future subframe. Secondly, there is a performance degradation in the Wi-Fi network in the TCP case compared with the UDP case. This degradation is due to the increased channel occupancy time that LTE-LAA uses when TCP is used. Both aspects affect the behaviour of the TCP congestion control mechanism, hence the degraded performance. It is also worth mentioning that after simulating and setting many parameters, it was observed that the coexistence performance is not affected by changing parameters such as the LAA ED threshold, LBT TxOP or the Z parameter associated to the HARQ based rule for the contention window size update. The practical impact of these parameters is not significant. As an example, different settings for the LAA ED threshold parameter are shown in Fig. 5. Moreover, the effect of changing other parameters has been studied such as the topology, number of users and number of cells. No significant impact on the performance was noticed.

V. Conclusion

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

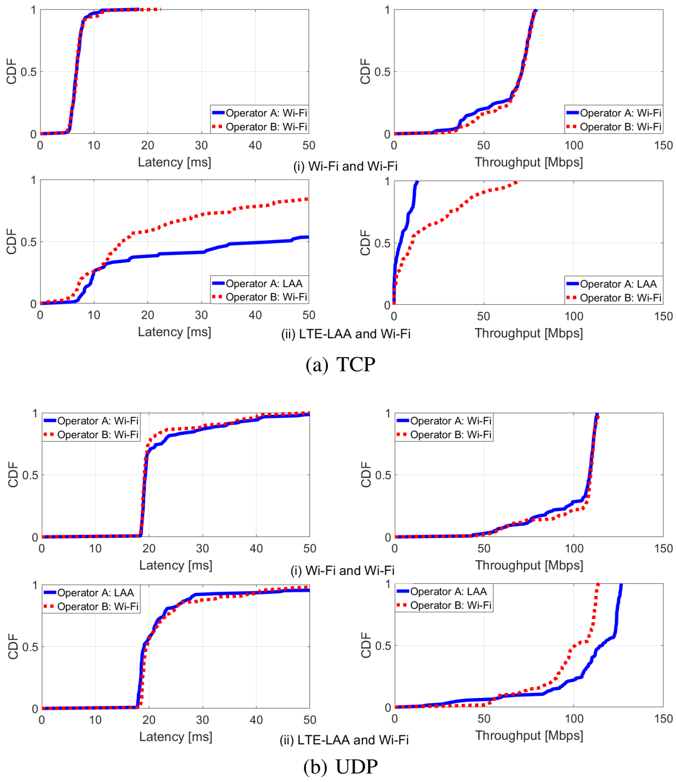

Fig. 4. Throughputs and latencies for LAA: (a) Using TCP, (b) Using UDP.

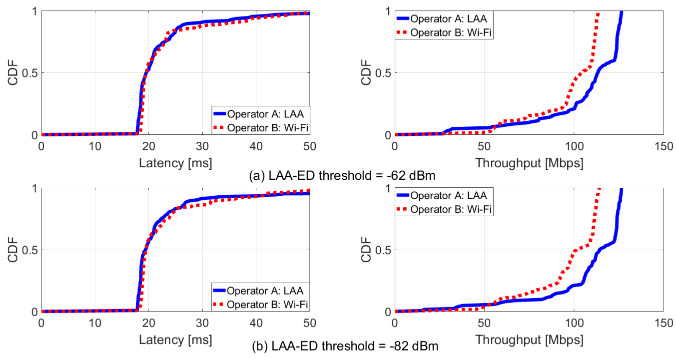

Fig. 5. Throughputs and latencies for LAA using different LAA ED thresholds: (a) -62 dBm, (b) -82 dBm.

References

[1] R. Ratasuk, N. Mangalvedhe, and A. Ghosh, "LTE in unlicensed spectrum using licensed-assisted access," in *Globecom Workshops (GC Wkshps), 2014*. IEEE, 2014, pp. 746–751.

[2] T. Irnich, J. Kronander, Y. Selén, and G. Li, "Spectrum sharing scenarios and resulting technical requirements for 5G systems," in *Personal, Indoor and Mobile Radio Communications (PIMRC Workshops), 2013 IEEE 24th International Symposium on*. IEEE, 2013, pp. 127–132.

[3] "The 3rd generation partnership project," available: http://www.3gpp.org.

[4] A. M. Cavalcante, E. Almeida, R. D. Vieira, F. Chaves, R. C. Paiva, F. Abinader, S. Choudhury, E. Tuomaala, and K. Doppler, "Performance evaluation of lte and wi-fi coexistence in unlicensed bands," in *Vehicular Technology Conference (VTC Spring), 2013 IEEE 77th*. IEEE, 2013, pp. 1–6.

[5] R. Kwan, R. Pazhyannur, J. Seymour, V. Chandrasekhar, S. Saunders, D. Bevan, H. Osman, J. Bradford, J. Robson, and K. Konstantinou, "Fair co-existence of licensed assisted access LTE (LAA-LTE) and Wi-Fi in unlicensed spectrum," in *Computer Science and Electronic Engineering Conference (CEEC), 2015 7th*. IEEE, 2015, pp. 13–18.

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

[7] N. Rupasinghe and İ. Güvenç, "Reinforcement learning for licensed-assisted access of lte in the unlicensed spectrum," in *Wireless Communications and Networking Conference (WCNC), 2015 IEEE*. IEEE, 2015, pp. 1279–1284.

[8] F. M. Abinader, E. P. Almeida, F. S. Chaves, A. M. Cavalcante, R. D. Vieira, R. C. Paiva, A. M. Sobrinho, S. Choudhury, E. Tuomaala, K. Doppler *et al.*, "Enabling the coexistence of LTE and Wi-Fi in unlicensed bands," *IEEE Communications Magazine*, vol. 52, no. 11, pp. 54–61, 2014.

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

[10] G. Ku and J. M. Walsh, "Resource allocation and link adaptation in LTE and LTE advanced: A tutorial," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 3, pp. 1605–1633, 2015.

[11] I. . W. Group *et al.*, "Part11: Wireless lan medium access control (MAC) and physical layer (PHY) specifications," *ANSI/IEEE Std. 802.11*, 1999.

[12] I. Qualcomm Technologies, "LTE in unlicensed spectrum: Harmonious coexistence with WiFi," 2014, available: http://www.qualcomm.com/media/documents/files/lte-unlicensed-coexistence-whitepaper.pdf.

[13] O. Sallent, J. Pérez-Romero, R. Ferrús, and R. Agustí, "Learning-based coexistence for LTE operation in unlicensed bands," in *Communication Workshop (ICCW), 2015 IEEE International Conference on*. IEEE, 2015, pp. 2307–2313.

[14] B. Jia and M. Tao, "A channel sensing based design for LTE in unlicensed bands," in *Communication Workshop (ICCW), 2015 IEEE International Conference on*. IEEE, 2015, pp. 2332–2337.

[15] A. K. Sadek, "Carrier sense adaptive transmission (CSAT) in unlicensed spectrum," Nov. 8 2016, uS Patent 9,491,632.

[16] I. Cable Television Laboratories, "Cablelabs perspectives on LTE-U coexistence with Wi-Fi and operational modes for LTE-U," 2014.

[17] 3rd Generation Partnership Project, "Feasibility study on licensed-assisted access to unlicensed spectrum; study on licensed-assisted access to unlicensed spectrum (release 13)," 2015, 3GPP TR 36.889 V13.0.0.

[18] A. Mukherjee, J.-F. Cheng, S. Falahati, L. Falconetti, A. Furuskär, B. Godana, H. Koorapaty, D. Larsson, Y. Yang *et al.*, "System architecture and coexistence evaluation of licensed-assisted access lte with ieee 802.11," in *Communication Workshop (ICCW), 2015 IEEE International Conference on*. IEEE, 2015, pp. 2350–2355.

[19] A. Bhorkar, C. Ibars, A. Papathanassiou, and P. Zong, "Medium access design for LTE in unlicensed band," in *Wireless Communications and Networking Conference Workshops (WCNCW), 2015 IEEE*. IEEE, 2015, pp. 369–373.

[20] J. Jeon, H. Niu, Q. Li, A. Papathanassiou, and G. Wu, "LTE with listen-before-talk in unlicensed spectrum," in *Communication Workshop (ICCW), 2015 IEEE International Conference on*. IEEE, 2015, pp. 2320–2324.

[21] A. Damnjanovic, N. Bhushan, W. Chen, T. Luo, J. Tingfang, Y. Wei, D. P. Malladi, and P. Gaal, "Techniques for assessing clear channel in an unlicensed radio frequency spectrum band," Jul. 25 2014, uS Patent 20150098397A1.

[22] F. S. Chaves, E. P. Almeida, R. D. Vieira, A. M. Cavalcante, F. M. Abinader, S. Choudhury, and K. Doppler, "LTE UL power control for the improvement of LTE/Wi-Fi coexistence," in *Vehicular Technology Conference (VTC Fall), 2013 IEEE 78th*. IEEE, 2013, pp. 1–6.

[23] ns 3 Project, "ns-3 manual: Release ns-3-dev," Oct. 4 2016, available: http://www.nsnam.org/docs/release/3.26/manual/ns-3-manual.pdf.

[24] ——, "The ns-3 wi-fi module documentation: Release ns-3-dev," Jan. 12 2016, available: http://www.nsnam.org/docs/models/html/wifi.html.

[25] ——, "The ns-3 lte module," 2014, available: http://www.nsnam.org/docs/models/html/lte.html.