Impact of changing energy detection thresholds on fair coexistence of Wi-Fi and LTE in the unlicensed spectrum

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Abstract*—The exponential increase in the number of mobile devices in use today has led to a commensurate increase in the demands on both cellular and Wi-Fi infrastructure, thus requiring that both licensed (cellular) and unlicensed (Wi-Fi) spectrum be utilized as efficiently as possible. One solution being actively pursued by industry is for cellular systems to use the unlicensed spectrum in addition to the licensed spectrum, which would require fair coexistence with Wi-Fi in the unlicensed spectrum. As per the IEEE 802.11 standard, Wi-Fi uses an energy detection (ED) threshold of -62 dBm when Long Term Evolution-Licensed Assisted Access (LTE-LAA) and/or Long Term Evolution Un-Licensed (LTE-U) nodes are deployed close by, whereas the LTE-LAA specification recommends that LTE-LAA detect Wi-Fi at -72 dBm. In our work, we evaluate the effect of this asymmetry in the ED threshold on coexistence between the two systems. We develop a coexistence simulator in ns-3 and vary both the Wi-Fi and LTE energy detection thresholds and demonstrate that lowering the Wi-Fi ED threshold from -62 dBm improves performance for both Wi-Fi and LTE-LAA. Prior work has mostly focused on determining the ED threshold that should be used by LTE-LAA/LTE-U. As far as we are aware, this is the first result that demonstrates that lowering the Wi-Fi ED threshold improves performance for *both* systems. The conclusion is that if Wi-Fi treats LTE-LAA/LTE-U as it would an overlapping Wi-Fi, coexistence performance improves compared to the current assumption that Wi-Fi treats LTE-LAA/LTE-U as noise.

***Index Terms*—LTE, Unlicensed spectrum, Wi-Fi.**

I. INTRODUCTION

The rapid proliferation of high-bandwidth smartphones, tablets and other smart devices has led to an extremely high demand for spectrum in order to cater to end user needs, resulting in a so-called spectrum-crunch. Cellular systems are heavily overloaded at crowded or densely populated regions such as university campuses, sporting events and stadiums. It is also expected that the global mobile traffic will increase two-fold every year and the volume of traffic carried by wireless networks is expected to be 1000 times higher than that of 2010 by 2020. In an attempt to solve the spectrum-crunch problem, mobile operators are trying to optimize the use of their limited allocated spectrum as much as possible by deploying Long-Term Evolution (LTE) small cells (*i.e.,* femto and pico cells) under a single macro Base Station (BS). However, excessive reuse of the same spectrum increases interference and leads to a decrease in cellular performance. Hence, cellular operators seeking to provide alternative solutions to satisfying user bandwidth demands with low capital expenditure (CAPEX) are considering the use of free unlicensed spectrum (e.g., ISM bands) by the existing LTE licensed network. This creates a coexistence scenario where devices are operating on the same spectrum with different technologies, LTE and Wi-Fi in this case, and suitable coexistence schemes that are fair to both need to be developed.

There are currently two specifications of LTE that will allow it to coexist with Wi-Fi in the 5 GHz unlicensed band. They are Licensed Assisted Access (LTE-LAA) and LTE-Unlicensed (LTE-U). LTE-LAA is a standardized solution that was developed within the 3rd Generation Partnership Project (3GPP) [1] and specifies a Listen-Before-Talk (LBT) mechanism, like Wi-Fi. On the other hand, LTE-U [2] was proposed by Qualcomm and is a proprietary system which does not implement LBT but instead employs a duty-cycling approach along with a channel sharing mechanism called Carrier Sense Adaptive Transmission (CSAT) that adapts the LTE-U duty cycle according to the Wi-Fi load on the channel. In the U.S. the spectrum rules do not mandate LBT in the 5 GHz band and hence the approach taken by LTE-U is reasonable. However, in the rest of the world, LBT is mandated for coexistence, and hence LTE-LAA was developed. As currently specified, both LTE-LAA and LTE-U utilize carrier aggregation between its licensed network and the unlicensed one and all uplink traffic is transmitted on the licensed carrier. In our work, we are interested in LTE-LAA and LTE-U spectrum access scheme on the unlicensed network only and in ensuring fair access between Wi-Fi and LTE. As per 3GPP, this fairness can be defined in three ways: air-time access at the transmitter, user level throughput (ULP) at the receiver and latency at the receiver.

Realistic deployments today are extremely dense, making fair-sharing coexistence studies difficult in both simulation and deployment. In addition to the metrics mentioned above (*i.e.,* air-time, ULP and latency) other challenges that arise such as hidden nodes between different technologies, the impact of LTE control signals, effect of resource allocation and scheduling on coexistence, frequent back-offs etc. need to be studied in realistic scenarios. Most existing studies on the impact of coexistence use simulators like MATLAB where it

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is difficult to model dense deployment scenarios. In order to study the throughput performance up to the application layer we need a simulator which includes the protocol stack. Hence, in this paper we investigate coexistence mechanisms using the ns-3 simulator, where we can also consider effects such as hidden nodes.

This paper is organized as follows. Section II describes the state-of-art in coexistence studies of LAA/LTE-U and Wi-Fi. The coexistence system model and assumptions are described in Section III, followed by the experimental setup and results in Section IV and conclusions in Section V.

II. RELATED WORK

The increased interest in LTE/Wi-Fi coexistence in the unlicensed bands from both industry and academia has led to a number of recent research and standardization activities. In [3] and [4], the authors analyze both LTE-LAA and LTE-U and show that optimal configurations of both approaches are capable of providing similar levels of fairness to Wi-Fi and the choice between CSAT and LBT is solely driven by the LTE operators' interest and governmental regulation. In order to coexist with Wi-Fi, authors of [5] propose a new functionality required for LAA-LTE which includes a mechanism for channel sensing based on LBT and discontinuous transmission on the carrier with limited maximum transmission across multiple unlicensed channels. In [6], a design for the LBT mechanism for LAA-LTE to ensure that it operates at least as fairly as Wi-Fi in unlicensed spectrum is proposed. In [7], the authors focus on various design aspects of LBT schemes for LAA that aim to emulate the contention based scheme in Wi-Fi as a mean of providing equal opportunity channel access for both of these technologies.

Authors of [8] explore the impact of a MAC layer solution which allows graceful co-channel co-existence. In [9] authors present an analytical framework to investigate the downlink coexistence performance between LBT and LAA. Using this framework, an analysis based on Markov chains is developed and downlink throughput is analyzed. In [10], the authors propose fairness between Wi-Fi performance loss ratio and LTE-U duty cycle. Depending upon whether the SINR is above or below -62 dBm, authors classify LTE-U as strong or weak. In [11] authors dedicate the contention free period to LTE-U users and allow a contention period to traditional Wi-Fi users. Also authors investigate the optimization of joint user association and resource allocation to further improve system throughput and user fairness. In [12] authors reused the concept of almost blank sub-frame (which is proposed in LTE standards) to the LTE and Wi-Fi coexistence.

In [13], the authors have studied the impact of LTE and Wi-Fi coexistence using the ns-3 simulator but the analysis does not show in detail what the impact on different threshold values is and how the channel gains access by LTE-LAA once the medium is won. Most of the above work has focused on methods that LTE-LAA and LTE-U can use to ensure fair coexistence, without considering changes that Wi-Fi can implement to improve coexistence. In this paper we explore in detail one particular parameter that Wi-Fi could change to improve coexistence, and that is the energy detection threshold. We use ns-3 to perform a thorough analysis of LTE-LAA, LTE-U and Wi-Fi coexistence with respect to the choice of energy detection threshold.

III. DISCUSSIONS ON COEXISTENCE

In this section, we describe the system model for the rest of the paper and the hidden node challenges in LTE/Wi-Fi coexistence.

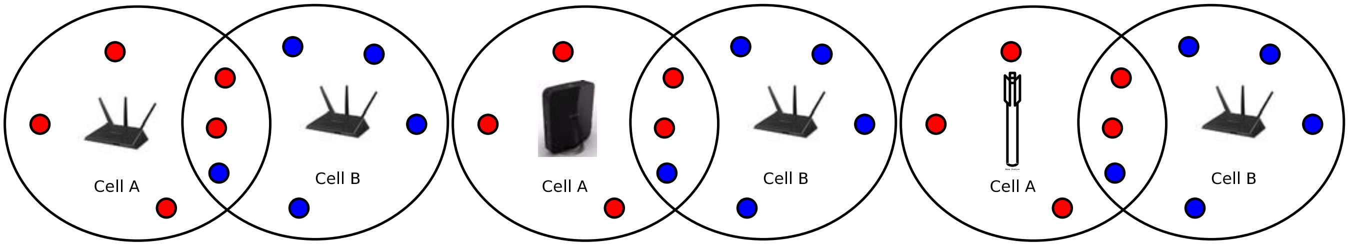
A. System Model and Assumptions:

We assume that the cellular BS (either LTE-LAA or LTE-U) will be using the unlicensed spectrum for downlink only data transmissions, which will be shared with a co-channel Wi-Fi access point (AP). The control information and any uplink data is always transmitted using licensed spectrum. We assume that LTE-LAA will follow the Load Based Equipment (LBE) mechanism while accessing the unlicensed spectrum and LTE-U will follow the fixed duty cycle mechanism based on the traffic load. Hence, there will be always fair sharing of unlicensed spectrum (*i.e.,* $\frac{1}{N}$ where, N is the number of unlicensed BS deployed nearby) among operators. We assume there is no central controller that will handle coordination between the different LTE cellular BSs and Wi-Fi APs. Hence, our approach is distributed in nature. Each LTE-LAA BS or Wi-Fi AP will follow the LBT Carrier Sense Multiple Access (CSMA) mechanism for accessing the medium, while LTE-U will use a duty-cycling approach. The traffic is assumed to be Poisson with parameter λ.

B. Hidden Node Problem:

In a Wi-Fi network that uses CSMA, hidden nodes occur when a node is visible to an AP but other neighboring nodes cannot hear its transmissions to the AP. Due to different sensitivity thresholds (-62 dBm, -72 dBm, -82 dBm) being used to protect against different systems, the hidden node problem is more severe in LTE-/Wi-Fi coexistence. Wi-Fi uses -82 dBm to protect other Wi-Fi users and -62 dBm to protect all other users of the spectrum (including LTE-LAA and LTE-U). LTE-LAA has specified -72 dBm as the energy detection threshold to be used to protect Wi-Fi while the latest LTE-U specification uses -62 dBm as the protection level against Wi-Fi. Some of the coexistence scenarios that can arise using a combination of these values are outlined below:

- **LTE-LAA ED of -62 dBm, Wi-Fi ED of -62 dBm:** Using an ED threshold of -62 dBm for both LTE-LAA and Wi-Fi may result in hidden node problems as the distance between the LTE-LAA BS and the Wi-Fi AP increases. A transmitted signal might still be strong enough to cause interference to a user on the overlapping cell, while detected as a weak signal by its BS or AP, rendering it invisible. Acknowledging this problem, LTE-LAA reduced its ED specification to -72 dBm while Wi-Fi still maintains the -62 dBm threshold leading to an



(a) (b) (c)

Fig. 1: (a) Cell A and Cell B use Wi-Fi, (b) Cell A switches to LTE-LAA and (c) Cell A switches to LTE-U

asymmetry which may still create coexistence problems. We will study this later on in the paper.

- **LTE-LAA ED of -82 dBm, Wi-Fi ED of -82 dBm:** If both LTE-LAA and Wi-Fi set their detection threshold to -82 dBm, they become more sensitive to interference and the hidden node problem may be solved. But it may cause the AP to become too sensitive to interference and backing off when it does not need to, which could then lead to reduced throughput performance. We will show however that this setting actually improves coexistence performance for both systems.
- **LTE-LAA ED of -82 dBm, Wi-Fi ED of -62 dBm:** The Wi-Fi alliance has proposed that LTE-LAA should lower its threshold to - 82 dBm and hence this asymmetrical detection threshold situation is an interesting one to investigate. It may actually worsen Wi-Fi throughput performance since the Wi-Fi cell is now less sensitive to interference than the LTE-LAA cell.

Fig. 1a shows both Cell A and Cell B using Wi-Fi, where the users associated with Cell A and Cell B are denoted by red and blue respectively. Fig. 1b shows Cell A switching to LTE-LAA and Fig. 1c shows Cell A switching to LTE-U. In this paper, we evaluate varying energy detection thresholds in these three scenarios thoroughly.

IV. EXPERIMENTAL RESULTS AND ANALYSIS:

In this section, we describe the various experiments simulated and analyze the results.

A. Experiment Setup

The system model described in Section III is simulated using a ns-3 simulator. Table I shows the simulation parameters used. We consider an indoor system with two BSs or APs each of which are 3 m in height with a coverage of 150 m. The transmit power of the cellular BS, Wi-Fi AP, LTE user equipment (UE) and Wi-Fi station (STA) are all set at 18 dBm and the UE/STA noise figure is 5 dB. There are two steps in each experiment:

- **Step 1:** Cell A and Cell B both use Wi-Fi
- **Step 2:** Cell A switches to LTE-LAA or LTE-U and Cell B continues using Wi-Fi.

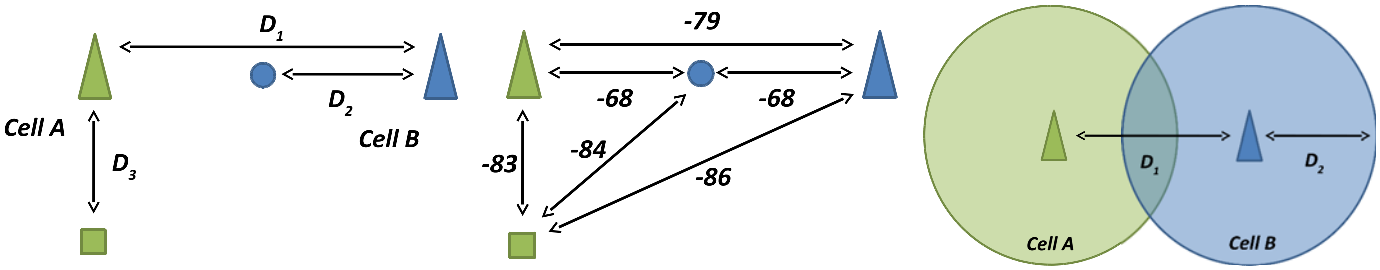
The objective is to study the effects of the switch on both Cell A and Cell B. For LTE-LAA we vary the energy detection threshold ED_L, for LTE-U we vary the duty cycle and for Wi-Fi the clear channel access (CCA) energy detection threshold ED_W. Data is transmitted according to the FTP Model 1 traffic, which is specified by 3GPP, over UDP layer. In order to simulate fully loaded data traffic, the parameter of the Poisson distribution is set to 2.5. The Wi-Fi network uses a single antenna (Single-Input-Single Output, SISO), does not use the Request-to-Send/Clear-to-Send (RTS/CTS) mode and aggregation is turned off. Both Wi-Fi and LTE-LAA operate on 5.180 GHz, with a bandwidth of 20 MHz. The rate adaptation for Wi-Fi network is controlled by an 'ideal' rate control algorithm, where the BS will schedule a rate based on SNR feedback from the station. Each simulation is executed for 48 seconds and repeated three times with different seeds on the random number generator.

We conduct three different experiments as follows.

- **Experiment #1** is a simple experiment with only one user in each cell. As shown in Fig. 2a, the Cell B user is in between BS A and BS B, where the distance between BS A and BS B is fixed and defined as D_1. We vary the distance, denoted D_2, between the Cell B user and BS B, and consequently the distance between it and BS A as well. We denote the distance between the Cell A user to its BS A as D_3, and it is deployed perpendicular to the line joining BS A and BS B. We set up the experiment in this fashion in order to to highlight the effect of the hidden node problem on a single Wi-Fi user. Then, we switch the position of both cells STA (*i.e.,* Cell A STA is in between Cell A and B BS, Cell B STA is perpendicular to its BS) so we can observe the effect of the hidden node problem on a single LTE-LAA user. As shown in Fig. 2b, we observe that for D_1 = 75 m, each BS receives the other at a signal strength of -79 dBm. Therefore, varying the ED_W and ED_L from -62 dBm to -82 dBm will give different performance. Fig. 3 shows the heat map of signal strength with Experiment #1.
- **Experiment #2** more appropriately reflects a real deployment. As shown in Fig. 2c, a number of users (20 for each cell) are uniformly distributed in a circular area with the BS in the center, with a maximum radius of deployment D_2. We vary the distance between both BS (denoted by D_1) to observe the hidden node problem. ED_W and ED_L are individually varied between -62 dBm, -72 dBm,

TABLE I: Simulation Parameters

Parameters	Experiment # 1	Experiment # 2
ED_L	-62, -82 dBm	-62, -72, -82 dBm
ED_W	-62, -82 dBm	-62, -72, -82 dBm
D_1	75 m	25, 50, 75, 100, 125, 150 m
D_2	12.5, 25, 37.5, 50, 62.5 m	75 m
D_3	50 m	M/A
No. of users for each cell	1	20
BS transmit power	18 dBm	18 dBm
BS antenna gain	0 dB	5 dB
UE/STA transmit power	18 dBm	18 dBm
UE/STA antenna gain	0 dB	0 dB
Noise figure	5 dB	5 dB
RTS/CTS	Not enabled	-
A-MPDU	Not enabled	-
LTE & Wi-Fi antenna mode	SISO	SISO
Operating frequency	5.180 GHZ	5.180 GHZ
Wi-Fi rate control	Ideal Wi-Fi manager	Ideal Wi-Fi manager
LAA rate control	Proportional Fair (PF)	Proportional Fair (PF)
Traffic	UDP	UDP
Full buffer (saturation)	Yes	Yes
Simulation time	48 s	48 s



(a)

(b)

(c)

Fig. 2: (a) Experiment #1, (b) Received signal strength (in dBm) for Experiment #1, with D_1 = 75 m, D_2 = 37.5 m, and D_3 = 100 m (c) Experiment #2 and #3;

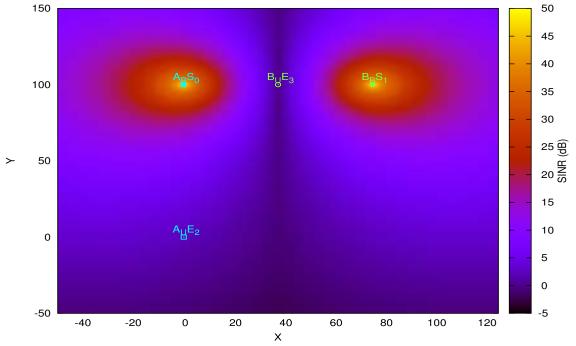


Fig. 3: Signal strength heat map of Experiment #1, with D_1 = 75 m, D_2 = 37.5 m, D_3 = 100 m.

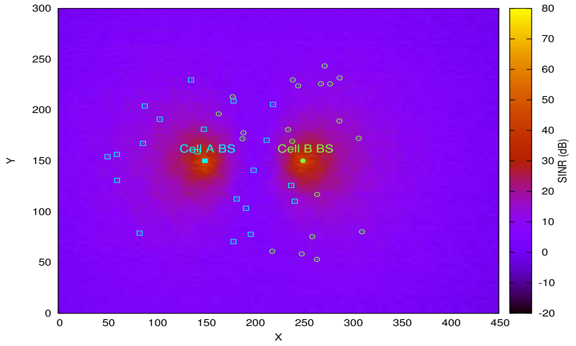


Fig. 4: Signal strength heat map of Experiment #2, with $D_1 = 100m$, $D_2 = 100m$

and -82 dBm in order to observe the effect as a function of D_1. Fig. 4 shows the heat map of the received signal strength of each user.

- **Experiment #3** uses LTE-U with duty cycling instead of LTE-LAA in Cell A in Step 2 of the experiment. This experiment uses the same parameters as the Experiment #2, with the ED_L parameter omitted. Instead, we vary the duty cycle coefficient over the values 0.3, 0.5, and 0.7 to study the effect on coexistence.

For each of the above experiments, we use the following performance metrics to study the effects of varying the parameters on users in each BS:

- **Mean throughput:** The average throughput over multiple file transfers is calculated as number of total successfully received bytes divided by total transmission time.

- **Mean Latency:** The average of latency over multiple file transfers is calculated from time of packet arrival in the MAC buffer to successful transmission (including re-transmission).

B. Results and Analysis:

*1) **Experiment #1**:*

Cell B performance: Here, the user of Cell B is in-between Cell A and Cell B as shown in Fig. 2a. Fig. 5a shows the mean throughput of Cell B for Steps 1 and 2 of the experiment for different combinations of ED_W and ED_L. From the perspective of Cell B which is always using Wi-Fi, fair coexistence with LTE-LAA is when its throughput remains more or less the same when Cell A switches from Wi-Fi in Step 1 to LTE-LAA in Step 2. From Fig. 5a, we observe that the throughput performance in Step 2 that is closest to that of Step 1 is when ED_W = -82 dBm, regardless of the ED_L value, i.e. the main determination of Wi-Fi performance is its own sensing level in the presence of LTE-LAA rather than the sensing level used by LTE-LAA. This is a very important result since most existing work attempts to show that the sensing level used by LTE-LAA is the deciding factor for Wi-Fi performance. Since the BSs are receiving each others signal at -79 dBm, setting ED_W to -82 dBm will enable Cell B to back-off to Cell A in the same way irrespective of whether Cell A is using Wi-Fi or LTE-LAA, and hence the overall throughput remains stable. Setting ED_W to -82 dBm will make the Wi-Fi network treat the LTE-LAA as a peer in terms of channel occupancy. Only when D_2 is small (12.5 m) does Cell B achieve a higher throughput with ED_W = -62 dBm than with -82 dBm. This is because the received signal strength is higher due to the close proximity to the Cell B BS and transmissions are successful even in the presence of interference from Cell A. Fig. 5b shows the latency results, which are inversely proportional to the throughput results on all ED_W and ED_L values, as expected. Again, Cell B achieves the lowest latency with ED_W = -82 dBm in Step 2, close to the latency of Step 1.

Cell A performance: Here, the user of Cell A is in-between Cell A and Cell B. As shown in Fig. 6a, we observe an increase in overall throughput performance for Cell A when it switched to LTE-LAA. Similar to the Cell B performance, we also observe that the best throughput result are obtained with ED_W value of -82 dBm, with both ED_L value -62 dBm and -82 dBm showing similar result. We observe that the high performance of LTE-LAA compared to Wi-Fi is due to the efficiency of the LTE physical layer. The latency results shown on Fig. 6b consistently shows an inverse proportion to the throughput results, with the best latency results also obtained with ED_W value of -82 dBm on both ED_L value.

In both of the above experiments, we notice that only the Wi-Fi ED threshold value affects the performance. Setting ED_W to -62 dBm in Step 2 causes the Wi-Fi cell to back-off less frequently to Cell A as compared to Step 1 when both cells are using Wi-Fi and backing off at -82 dBm, thus resulting in reduced throughput. We also notice from Fig. 6a that the throughput in Cell A increases about 6 times when it switches to LTE-LAA from Wi-Fi while the latency reduces about 4 times. This is due to the better LTE-LAA physical layer (PHY) compared to Wi-Fi.

*2) **Experiment #2**:*

In this experiment, 20 users are deployed randomly around each BS with a maximum distance D_2 of 75 m. We vary D_1 which is the distance between the two BSs, ED_L which is the LTE-LAA energy detection threshold, and ED_W which is the Wi-Fi CCA detection threshold.

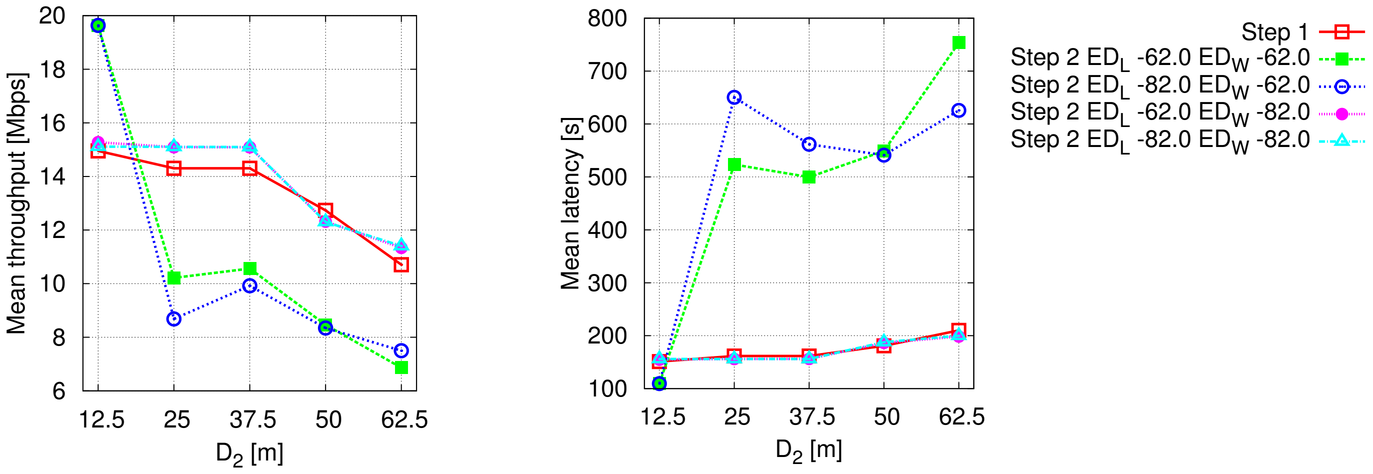
Fig. 7a and 7b show the mean throughput on Cell A and Cell B respectively as a function of D_1 for various combinations of ED_L and ED_W. In Step 1, when both cells are using Wi-Fi, the mean throughput is about 10 Mbps, i.e. the medium is being shared fairly. In Step 2, i.e. when Cell A switches to LTE-LAA, its throughput increases substantially about 5 times, which is similar to the result in Experiment #1. We also observe that the throughput of Cell B increases when Cell A switches to LTE-LAA, and the increase is greatest when ED_W = -82 dBm, i.e. when Wi-Fi treats LTE-LAA as it would treat another Wi-Fi. Since only a small fraction of users are subject to the hidden node problem of Experiment #1, the effect on the throughput is lower. Furthermore, the increase in the throughput and decrease in the latency of Cell A when it uses LTE-LAA, translates to more channel time available for Cell B to use. Similar to the results of Experiment #1, the ED_L value does not appreciably affect the throughput performance.

Fig. 8a and 8b show the latency results. On both cells, the lowest latency is achieved with ED_W of -82 dBm, followed by -72 dBm, and -62 dBm, while varying the ED_L value shows no significant difference. From Fig. 8a, we see that Cell A experiences a large decrease in latency when it switches to LTE-LAA. Cell B also shows improvement in latency when Cell A is using LTE-LAA.

*3) **Experiment #3**:*

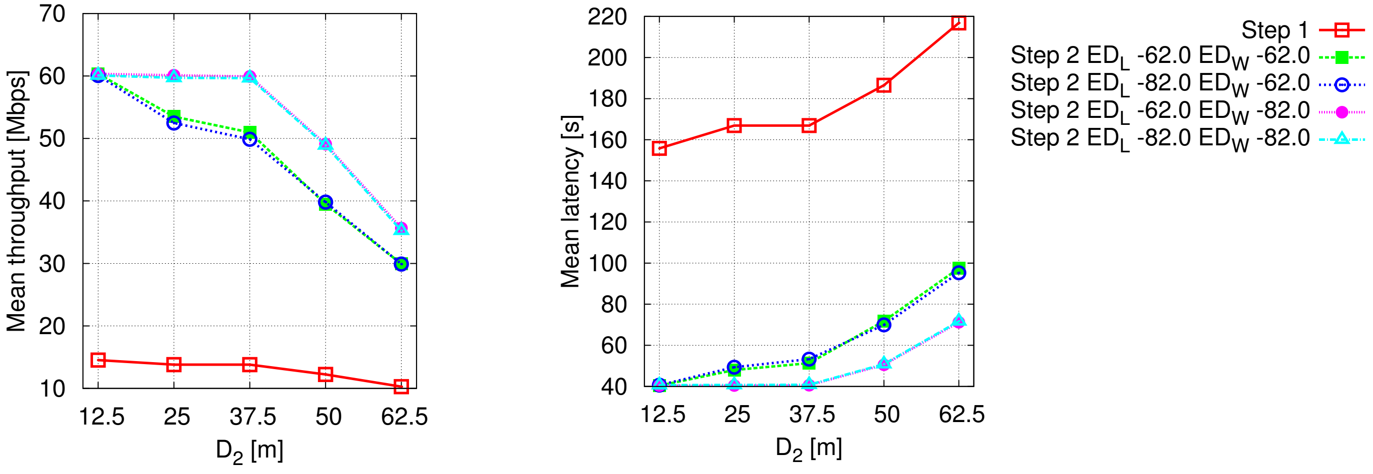
Similar to the previous experiment, Experiment #3 is set up using two cells and 20 STAs for each cell. The STAs are also deployed randomly in a radius of D_2, and both cell BSs are separated by a varied distance of D_1. On Step 1 of the experiment, both cells are using Wi-Fi and in Step 2, Cell A switches to LTE-U with a specified duty cycle (DC). We will study the effect of varying the duty cycle on LTE-U and the ED_W threshold of the Wi-Fi. Since LTE-U does not implement carrier sensing, the ED_L value is not used.

Figs. 9a, 9b, 9c and Figs. 10a, 10b, 10c presents the comparison of mean throughput across various DC and ED_W values for Cell A and Cell B, respectively. As the DC value increases in Step 2, the throughput performance of Cell A increases while it decreases for Cell B, as expected. Inter-



(a) (b)

Fig. 5: Experiment #1 for user in Cell B: (a) Mean throughput (b) Mean latency



(a) (b)

Fig. 6: Experiment #1 for user in Cell A: (a) Mean throughput (b) Mean latency

estingly, similar to the previous experiments, an ED_W value of -82 dBm maximizes throughput, though the effect is not as pronounced as in the experiments using LTE-LAA since when Wi-Fi coexists with LTE-U, the duty cycle is the primary factor in determining performance. Furthermore, comparing Figs. 9b and 10b, we see that a fair duty cycle value of 0.5 is actually not very fair to Wi-Fi.

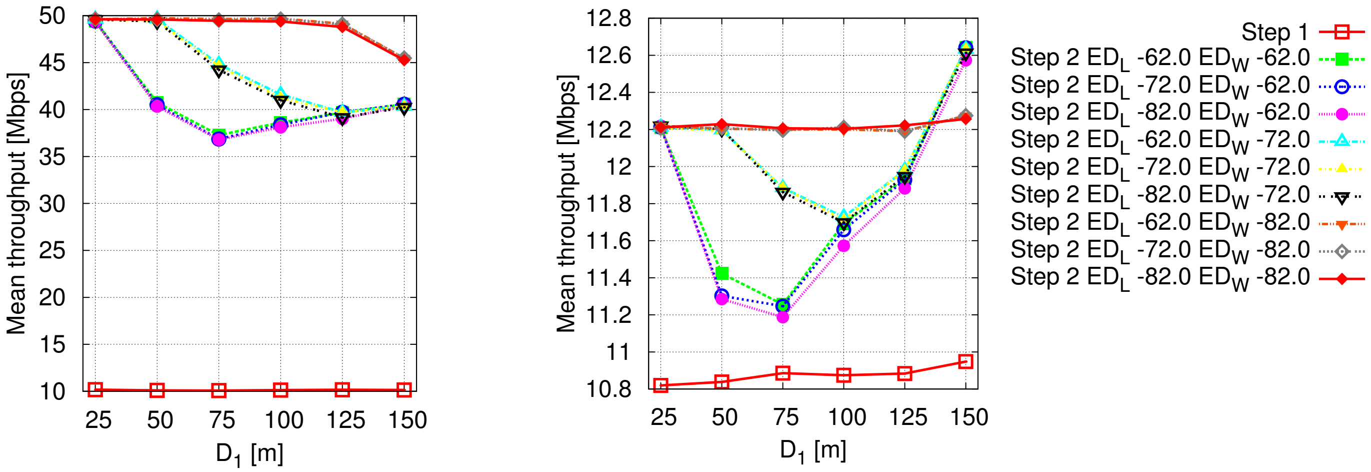
Figs. 10a, 10b and 10c show the mean throughput performance of Cell B for various ED_W and DC values. Again, an ED_W value of -82 dBm gives the highest throughput, similar to the results of Cell A. Since the DC is independent of received signal strength, when D_1 is small, Cell B backs off more and has lower throughput whereas Cell A has higher throughput since the DC is fixed. As D_1 increases, Cell B will back-off less and have higher throughput, thus interfering with Cell A and lowering its throughput.

Figs. 11a, 11b, 11c and Figs. 12a, 12b and 12c show the mean latency with various DC and ED_W values, for Cell A and B, respectively. Overall, Figs. 11a, 11b and 11c show huge decrease in mean latency for Cell A when it uses LTE-U. Despite its latency being lower compared to the LTE-LAA experiments, LTE-U has lower throughput since without carrier sensing, it will be more prone to interference from Cell B.

On the other hand, Figs. 12a, 12b, and 12c show a latency performance that is more aligned to our expectation, considering its throughput performance in Figs. 10a, 10b and 10c. We again observe that the lowest overall latency is obtained with ED_W of -82 dBm. As D_1 increases, the latency decreases and the throughput increases as shown in Figs. 10a, 10b and 10c.

V. CONCLUSIONS AND FUTURE WORK

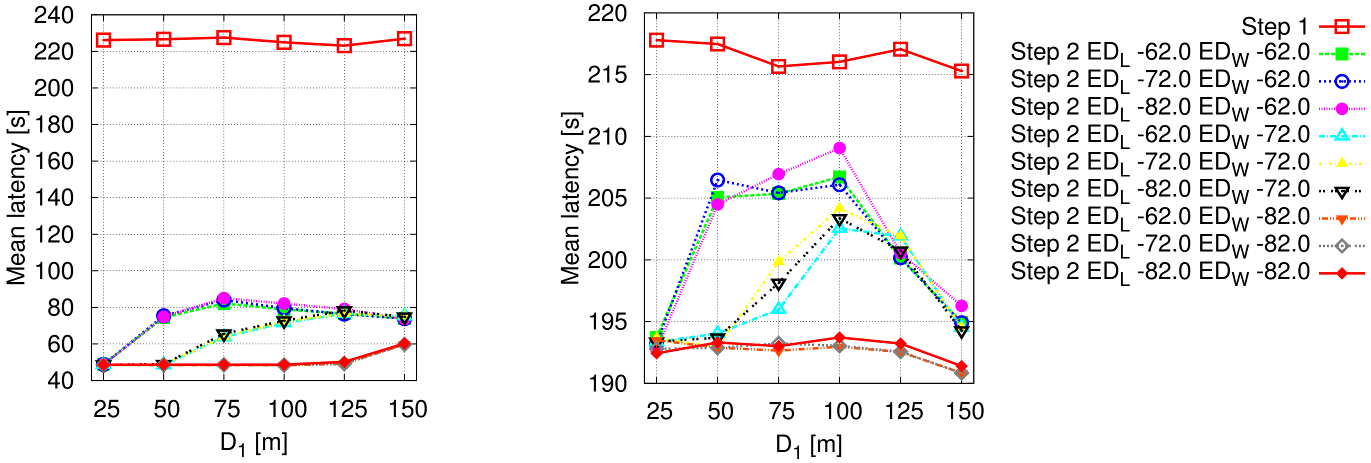
In this paper we have built a comprehensive simulation tool using ns-3 to study coexistence between Wi-Fi and LTE-



(a)

(b)

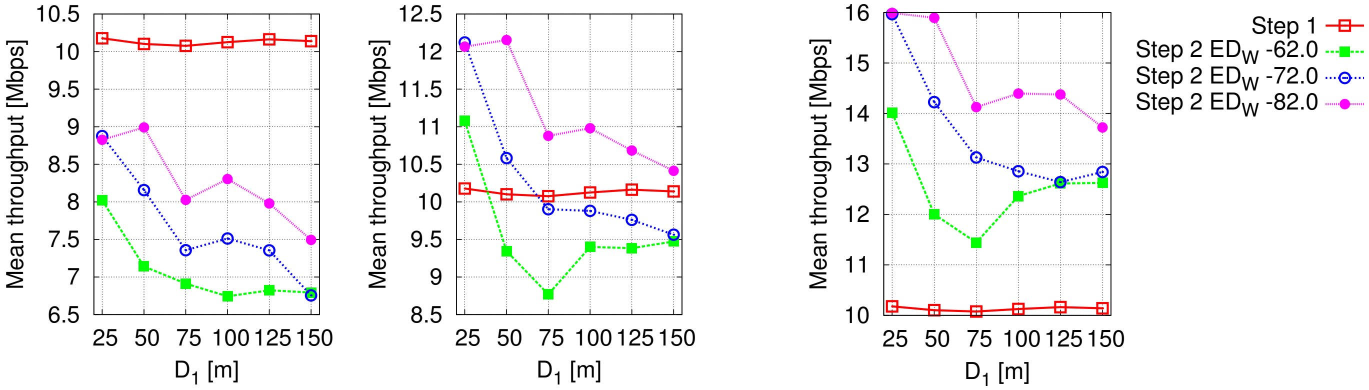
Fig. 7: Experiment #2 (a) Mean throughout of Cell A and (b) Mean throughput of Cell B



(a)

(b)

Fig. 8: Experiment #2 (a) Mean latency of Cell A and (b) Mean latency of Cell B

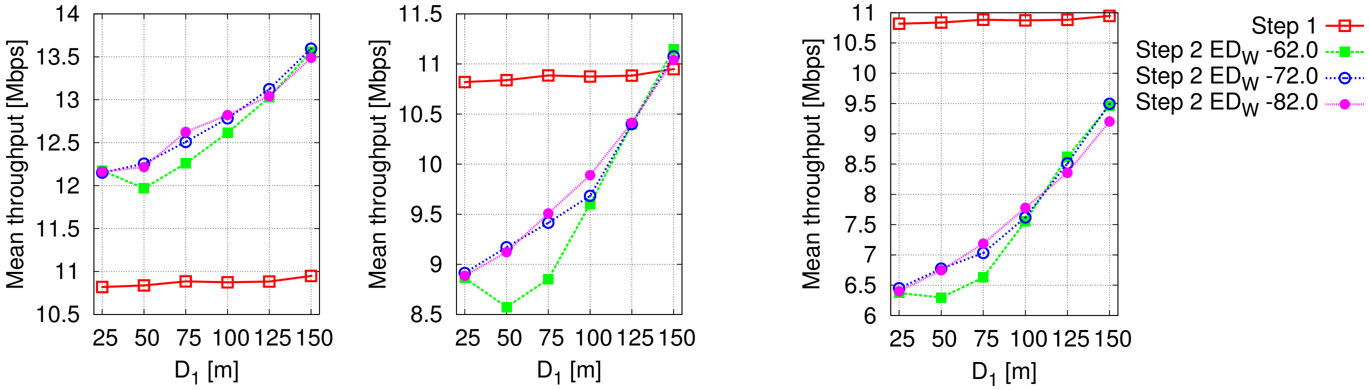


(a)

(b)

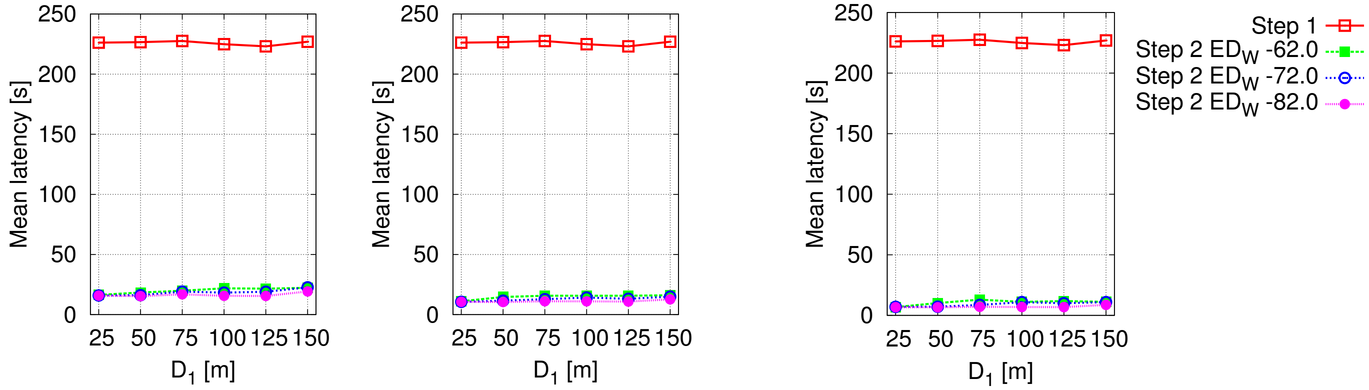
(c)

Fig. 9: Experiment #3, Cell A throughput (a) DC = 0.3, (b) DC = 0.5, and (c) DC = 0.7



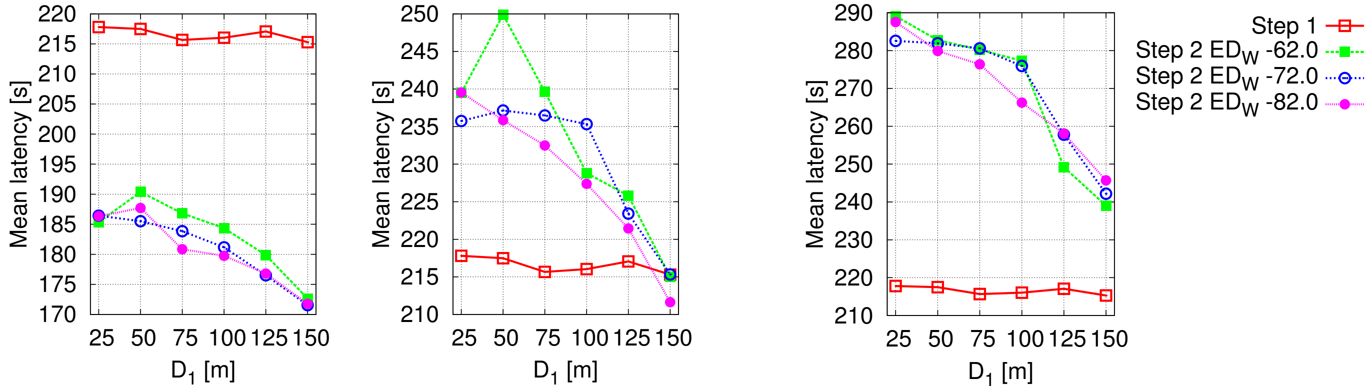
(a) (b) (c)

Fig. 10: Experiment #3, Cell B throughput (a) DC = 0.3, (b) DC = 0.5, and (c) DC = 0.7



(a) (b) (c)

Fig. 11: Experiment #3, Cell A latency (a) DC = 0.3, (b) DC = 0.5, and (c) DC = 0.7



(a) (b) (c)

Fig. 12: Experiment #3, Cell B latency (a) DC = 0.3, (b) DC = 0.5, and (c) DC = 0.7

LAA and Wi-Fi and LTE-U. The main results obtained from our extensive simulation study is that Wi-Fi, LTE-LAA and LTE-U all have improved throughput and latency performance when the energy detection threshold used by Wi-Fi in the presence of LTE is lowered to -82 dBm, *i.e.,* if Wi-Fi treats LTE-LAA and LTE-U as another coexisting Wi-Fi cell instead of as an interfering noise source. This result thus points to a coexistence scenario where Wi-Fi uses the same -82 dBm threshold to protect against Wi-Fi, LTE-LAA or LTE-U and continues to use -62 dBm against unknown noise or other interferers. In order for Wi-Fi to distinguish between LTE-U/LTE-LAA and other signals, Wi-Fi would need to implement LTE detection, which can be easily implemented by detecting the LTE synchronization signals. Future work will include LTE detection into the coexistence simulation. The studies in this paper used the basic SISO modes for both Wi-Fi and LTE. Future work will focus on incorporating the advanced modes such as Multiple Input Multiple Output (MIMO) as well as Multi-User MIMO (MU-MIMO). Furthermore, we only considered two overlapping BSs. Future work will extend to more overlapping cells, using combinations of Wi-Fi, LTE-LAA and LTE-U in realistic deployment scenarios.

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