Enhancing LAA/Wi-Fi Coexistence via Concurrent Transmissions and Interference Cancellation

Zhiwu Guo* Ming Li* Yong Xiao†
* Electrical and Computer Engineering, The University of Arizona, Tucson, USA
† School of Electronic Information and Communications, Huazhong University of Science and Technology, Wuhan, China
Email: {zhiwuguo, lim}@email.arizona.edu, yongxiao@hust.edu.cn

***Abstract*—With the rapid growth of mobile devices and popularity for data-intensive services, LTE Licensed-Assisted Access (LAA) has been proposed to allow coexistence of LTE and Wi-Fi in 5 GHz unlicensed band. Most existing works have been focusing on developing collision avoidance mechanisms to ensure the harmonious coexistence between Wi-Fi and LTE. In this paper, we argue that simply avoiding possible collisions caused by simultaneous transmissions does not fully utilize the unlicensed spectrum. We derive the optimal CCA threshold that enables as many simultaneous transmissions between coexisting LTE and Wi-Fi as possible and exploit successive interference cancellation to further increase the chance of concurrent transmissions. We introduce a Markov-model based approach to quantify the impact of energy detection, concurrent transmission and successful decoding probability on the throughput expressions of LAA and Wi-Fi. Extensive simulations have been presented to validate our proposed theoretical model. Our results show the throughput of Wi-Fi and LAA can be significantly improved under several typical coexistence scenarios.**

I. Introduction

To cope with the exponentially growing demand of mobile data services, FCC recently enables LTE operators to extend their services into the unlicensed national information-infrastructure (U-NII) bands [1] at 5 GHz, which has already been widely used by Wi-Fi systems. Developing efficient spectrum sharing strategies that can minimize cross-network interference and ensure a fair share of spectrum among all the coexisting devices is of critical importance for both LTE and Wi-Fi systems. To avoid collisions with other coexisting devices, the Wi-Fi system adopts carrier-sense multiple access with collision avoidance (CSMA/CA) [2]. In CSMA/CA, each device needs to first sense the channel and can only send signals if the channel is sensed to be idle. To allow harmonious coexistence between LTE and Wi-Fi, two solutions have been proposed by 3GPP: LTE Unlicensed (LTE-U) [3] and Licensed-Assisted Access (LTE-LAA) [4]. LTE-U is duty-cycle-based while LTE-LAA is contention-based. LTE-LAA has been considered as a long-term solution to enable coexistence between LTE and Wi-Fi. In this paper, we focus on coexisting mechanisms between LAA and Wi-Fi.

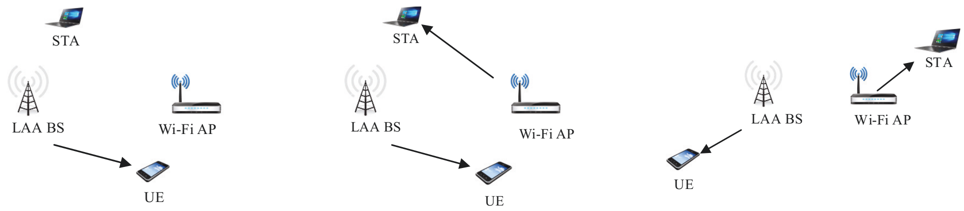
The work of Z. Guo and M. Li is partly supported by U.S. NSF grants CNS-1564477, CNS-1619728, CNS-1731164. The work of Y. Xiao is supported in part by National Key R&D Program of China grant 2016YFE0133000 and EU-China study on IoT and 5G grant EXCITING-723227.

A. Motivation

Most existing works about LAA/Wi-Fi coexistence focus on developing mechanisms to adjust channel access time-sharing between LAA and Wi-Fi. In these mechanisms only one data transmitting device, e.g., LAA or Wi-Fi transmitter can access the channel at a given time instance. With an energy detection-based channel sensing scheme, this means that the energy detection threshold of LAA or Wi-Fi must be set to be sufficiently low so that co-locating Wi-Fi and LTE users can always detect each other. In particular, 3GPP recommends energy detection threshold (CCA) of LAA to be -72 dBm [4], and the CCA threshold of Wi-Fi 802.11ac to be -62 dBm [2].

In this paper, we argue that the time sharing-based mechanism may result in inefficient utilization of the spectrum. More specifically, we investigate the potential performance improvement that can be achieved by allowing concurrent transmissions of two or more LAA and Wi-Fi transmitters. To alleviate the cross-interference between coexisting devices, we adopt interference cancellation techniques to cancel a certain amount of interference and improve the decoding success rate for both LAA and Wi-Fi links. In CSMA-based mechanisms, the concurrent transmissions can be enabled by adjusting the energy detection threshold of LAA or Wi-Fi. How the concurrent transmission and interference cancellation ability jointly impact the throughput of LAA/Wi-Fi? What should be the optimal CCA thresholds in different coexistence scenarios? In this paper, we have taken steps to address these problems.

As shown in Fig. 1 (a), traditionally to achieve harmonious coexistence of LAA and Wi-Fi, the CCA threshold of LAA/Wi-Fi must be set low enough to avoid cross-interference between coexisting systems. Therefore, LAA and Wi-Fi are located within the sensing range of the other, e.g. they can sense the transmission of each other, and most likely only one technology occupies the channel at any time. The total channel utilization of traditional LAA/Wi-Fi avoidance scheme in this example is 0.92 from our simulations, where we set CCA_w = -62 dBm, CCA_l = -72 dBm. In Fig. 1 (b), we investigate the same LAA/Wi-Fi coexistence scenario with Fig. 1 (a) but allow concurrent transmissions of LAA and Wi-Fi by increasing their CCA thresholds to CCA_w = -42 dBm and CCA_l = -40 dBm. Meanwhile, the STA and UE can employ interference cancellation techniques (such as SIC) to decode



(a) (b) (c)

Fig. 1: (a) Traditional LAA/Wi-Fi coexistence: collision avoidance, CCA_w = -62 dBm, CCA_l = -72 dBm, total channel utilization is 0.92; (b) Proposed concurrent transmission of LAA and Wi-Fi, CCA_w = -42 dBm, CCA_l = -40 dBm, total channel utilization is 1.6; (c) Concurrent transmission of LAA and Wi-Fi solves exposed terminal problem, CCA_w = -37 dBm, CCA_l = -37 dBm, total channel utilization is 1.84.

their signals of interest under concurrent transmissions, hence improving spectrum utilization. The total channel utilization is improved from 0.92 to 1.6, which is improved by 73.9%. In Fig. 1 (c), if we set CCA_w = -37 dBm and CCA_l = -37 dBm, LAA and Wi-Fi cannot detect each other but they can transmit concurrently and both decode successfully. The total channel utilization is 1.84, which is twice of that of Fig.1 (a). This is actually an exposed terminal scenario, which can be solved as a by-product of this work.

While there are many interference cancellation techniques, most of them are mainly suitable for homogeneous networks. Among the few that are applicable to heterogeneous networks, some of them require MIMO capabilities which may not be available at user's device. As a first step, in this paper, we use successive interference cancellation (SIC) as one example to showcase the possible improvement of spectrum utilization by allowing simultaneous transmission of co-locating LTE and Wi-Fi with interference cancellation techniques.

B. Main Contributions

The main contributions of this work are summarized as:

(1) We propose a novel LTE/Wi-Fi coexistence framework to improve the spectrum utilization efficiency by enabling concurrent transmissions between LAA and Wi-Fi by adjusting their CCA thresholds, whenever this is beneficial to enhancing the system's overall throughput. Using successive interference cancellation technique across two networks, we can further improve the performance in more coexistence scenarios.

(2) Due to imperfect cross-network energy detection, partially overlapping transmissions of LAA and Wi-Fi exist, bringing difficulties to model possible concurrent transmissions and calculate throughput. We address these challenges and introduce a Markov-model based approach to quantify the impact of energy detection, concurrent transmission, successful decoding probability on the throughput of LAA and Wi-Fi.

(3) Extensive simulations are conducted to validate the accuracy of the theoretical analysis. We use several typical coexistence scenarios to show that LAA and Wi-Fi's total throughput can be significantly improved compared with interference avoidance, and optimal CCA thresholds are derived in each case.

(4) We also discuss potential practical issues on implementing our scheme and present possible solutions to address them, such as local channel monitoring and implicit communication.

II. Related Work

Most existing works of LTE/Wi-Fi coexistence have been focusing on collision avoidance-based fairness mechanism design between coexisting systems. Cavalcante et al. [5] simulate LAA/Wi-Fi coexistence and show that the throughput of LAA is not affected much, while Wi-Fi throughput is degraded greatly. Bianchi [6] provides a Markov model to compute the transmission probability and saturation throughput performance of the 802.11 distributed coordination function (DCF). Based on Bianchi's approach, some works [7]–[12] model the LAA/Wi-Fi coexistence. Gao et al. [7] established a Markov chain model to calculate the throughput and delay of Wi-Fi networks and Wi-Fi/LAA networks. The authors in [8], [9] investigate the throughput performance of different priority classes in coexisting Wi-Fi and LAA networks, using Markov model. Mehrnoush et al. [10] modified Bianchi'model to incorporate energy sensing threshold to evaluate the impact of threshold choices on throughput performance. However, no capture effect and concurrent transmissions are allowed. Yin et al. [11] adaptively adjusted the back-off window to satisfy the quality of service (QoS) of LAA network while minimizing the collision probability of Wi-Fi networks. The authors in [12] developed a model for the MAC delay distributions experienced by the Wi-Fi packets and LTE frames. Xiao et al. [13] developed a modified back-of-the-envelope method for LAA nodes to evaluate their accessing probabilities when coexisting with other wireless technologies, such as Wi-Fi.

Interference cancellation has attracted significant interest recently [14]–[18]. Yun et al. [18] proposed concurrent transmission of LTE and Wi-Fi, the receiver needs to have multiple antennas to decode LTE and Wi-Fi signal. Successive Interference Cancellation (SIC) [19] is proposed to be used in next-generation cellular networks where non-orthogonal multiple access (NOMA)is employed for multiple users to access radio, however, this technique was firstly adopted in homogeneous networks. In [17], SIC is adopted in Wi-Fi/ZigBee coexistence which belongs to heterogeneous networks coexistence scenario. Since Wi-Fi signal is typically much stronger than

Zigbee signal, receiver can decode Wi-Fi signal and Zigbee signal successively using SIC technique.

III. Preliminaries

In this section, the MAC protocol of Wi-Fi and LTE-LAA are briefly reviewed, while highlighting the differences of their contention/transmission parameters.

A. *Overview of Channel Access Mechanism for Wi-Fi and LAA*

Both Wi-Fi and LAA adopt Carrier-Sense Multiple Access (CSMA) to avoid collisions when multiple transmitters competing for accessing the same channel as illustrated in Fig.2.

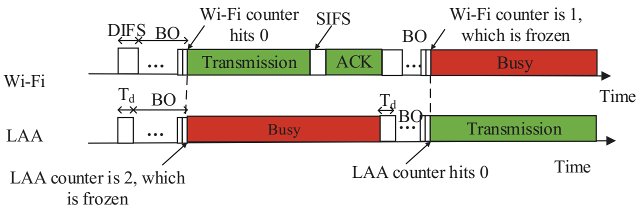


Fig. 2: Wi-Fi CSMA/CA (top) and LAA LBT (bottom) transmission timing diagrams, with collision avoidance.

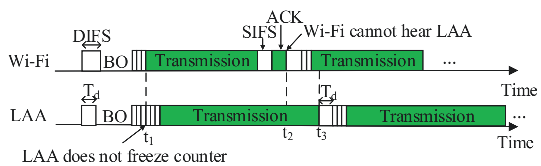


Fig. 3: Wi-Fi CSMA/CA (top) and LAA LBT (bottom) transmission timing diagrams, with concurrent transmission.

In particular, before each transmission, Wi-Fi devices need to check whether the channel is idle or not by performing carrier sensing (CS) for Wi-Fi transmissions and energy detection (ED) for non-WiFi transmissions. CS and ED are conducted for a certain period which is known as distributed inter-frame spacing (DIFS). If the channel is sensed idle for DIFS period, Wi-Fi transmitter will begin its back-off procedure. The back-off counter is generated uniformly from $[0, 2^j W_{min} - 1]$, where j is transmission stage, W_{min} is the minimum contention window of Wi-Fi system. The back-off counter is decremented by one each time slot σ. During the back-off process, Wi-Fi transmitter keeps monitoring channel to check whether it is idle, if the channel is sensed busy, Wi-Fi device has to freeze its back-off counter. The back-off counter will be resumed until the channel is idle for DIFS duration. The Wi-Fi transmitter will start transmitting packets when its back-off counter hits zero. Once Wi-Fi starts transmission, it can transmit for a duration called $TXOP_w$. After a successful transmission, a Wi-Fi receiver will send back an acknowledgment (ACK) to Wi-Fi transmitter followed by short inter-frame space (SIFS). Collision happens when back-off counters of two transmitters (either Wi-Fi or LAA networks) hits zero at the same time slot, in which case the contention windows of collided Wi-Fi transmissions will be doubled, namely $W_j = 2W_{j-1}$, however, there is a maximum contention window limit denoted as W_{max}, namely $W_j = W_{max}$ if $2^j w_{min} \geq W_{max}$. The collided packets will be re-transmitted until the maximum transmission limits are reached.

LAA uses the same mechanism for accessing the channel but with a different set of contention/transmission parameters. The main contention and transmission parameters of LAA [4] and 802.11ac [2] are summarized in Table I.

TABLE I: Channel access parameters of LTE-LAA/Wi-Fi.

	DIFS/T_d	W_{min}/W'_{min}	W_{max}/W'_{max}	TXOP
LAA	25 μs	4	8	2 ms
802.11ac	34 μs	4	8	1.504 ms

B. *Successive Interference Cancellation (SIC)*

Successive Interference Cancellation (SIC) is an effective technique for multiple receivers to decode their own interested signals when multiple transmitting signals are superimposed. The basic idea of SIC is that received signals are decoded sequentially while canceling already decoded signals from interference. Specifically, signal with the highest signal to interference and noise ratio (SINR) (the SINR should be equal to or greater than the minimum decoding threshold) can be firstly decoded while treating other unknown weak signals as interference. Then the signal with second-highest SINR can be decoded after the cancellation of the already decoded strongest signal, iteratively continue the above process until all the interested signal is decoded.

The decodability in each step of SIC depends on their received signal strength as well as their decoding thresholds. Suppose there are K concurrent transmissions in a receiver R, the received signal strength from highest to lowest are $S_1, S_2, \cdots, S_K$ respectively, namely $S_1 > S_2 > \cdots > S_K$, the noise power in receiver is N_0. R will firstly decode the strongest signal S_1, the SINR when decoding S_1 is

$$\gamma_1 = \frac{S_1}{\sum_{i=2}^{K} S_i + N_0}, \tag{1}$$

To successfully decode S_1, suppose the minimum decoding SINR threshold of R is θ, γ_1 has to satisfy

$$\gamma_1 \geq \theta. \tag{2}$$

If Eq. (2) is satisfied, R can proceed to decode S_2 while treating S_1 as known part, the SINR when decoding S_2 is

$$\gamma_2 = \begin{cases} \frac{S_2}{\sum_{i=3}^{K} S_i + N_0}, & \text{if } K \geq 3 \\ \frac{S_2}{N_0}, & \text{if } K = 2 \end{cases} \tag{3}$$

If $\gamma_2 \geq \theta$, R can successfully decode S_2, other users can be decoded following the similar process as shown in Eq. (3).

IV. System Model

Without loss of generality, we focus on downlink transmissions of both LAA and Wi-Fi systems under backlogged traffic conditions and refer to LAA and Wi-Fi receivers as UE and STA, respectively. We consider a scenario where N STAs and M UEs coexist in the same area.

Due to contention-based schemes (e.g. CSMA/CA and LBT) adopted in both Wi-Fi and LAA networks, Wi-Fi AP and LAA BS need to sense the channel in order to check channel availability before transmission. LAA BS (Wi-Fi AP) can transmit only when the detected energy strength is below its energy detection (ED) threshold, we denote the energy detection threshold of LAA and Wi-Fi as CCA_l, CCA_w respectively. In our model, we aim to enable concurrent transmissions of LAA and Wi-Fi by adjusting CCA of Wi-Fi or LAA. With the asymmetric received signal strength of interested signal and interference signal in UE or STA, SIC may enable them to successfully decode their interested signals even when LAA BS and Wi-Fi AP transmit simultaneously.

In Fig. 3, we show an example of how CSMA/CA and LBT protocol work when CCA_w = -37 dBm, CCA_l = -37 dBm, in this case, Wi-Fi AP and LAA BS nearly cannot detect each other. In time slot t_1, t_3, although there is an ongoing Wi-Fi transmission, since LAA cannot hear the Wi-Fi transmission, it will continue decreasing the back-off counter; in time t_2, although there is an ongoing LAA transmission, Wi-Fi also does not freeze its back-off counter since it cannot hear LAA transmission. We do not show the ACK of LAA in Fig. 3 since the ACK of LAA is transmitted in its licensed band. We assume that ACKs of Wi-Fi can always be delivered reliably using an out-of-band channel. Besides, at most one user is active in Wi-Fi or LAA system in a specific time instance, each user is randomly scheduled to receive the signal from its transmitter. For high CCA threshold of LAA or Wi-Fi, LAA or Wi-Fi may not hear the transmission of the other. Therefore, LAA BS or Wi-Fi AP may bring interference to the receiver of the other network.

A. *Successful Decoding Probability of UE and STA*

We need to obtain the successfully decoding probability of the receiver under concurrent transmission. Let the transmission power of LAA BS and Wi-Fi AP P_l, P_w respectively, the minimum successfully decoding SINR threshold of LAA and Wi-Fi are θ_l, θ_w respectively.

For simplicity, we only present how to derive the SINR distribution of UE. Since at any time there are at most two links that may interfere with each other , the received SINR of UE should satisfy:

$$\gamma_l^1 = \frac{P_l|h_l|^2}{N_0 + P_w|h_l'|^2} > \theta_l, \quad (4)$$

or

$$\gamma_l^2 = \frac{P_w|h_l'|^2}{N_0 + P_l|h_l|^2} > \theta_w, \gamma_l^3 = \frac{P_l|h_l|^2}{N_0} > \theta_l. \quad (5)$$

where N_0 is the power of white noise. h_l, h_l' are interested signal channel (LAA BS to LAA UE) and interference signal channel (Wi-Fi AP to LAA UE), including small scale fading and large scale path loss. We assume a Rayleigh channel model which is commonly used for LTE and Wi-Fi, and the channel state information (CSI) does not fluctuate within one transmission period (TXOP). Rewrite Eq. (4) as

$$\gamma_l^1 = \frac{S_l}{N_0 + S_l'}, \quad (6)$$

The received power distribution for Rayleigh channel h_l, h_l' are exponentially distributed with mean $p_l d_l^{-\alpha}, p_w {d_l'}^{-\alpha}$, where d_l, d_l' are distance of LAA BS and LAA UE, Wi-Fi AP and LAA UE respectively, α is path loss factor. We can easily obtain the probability of $Pr(\gamma_l^1 > \theta_l)$ by calculating the cumulative distribution function of Eq. (6), shown as

$$Pr(\gamma_l^1 > \theta_l) = \exp[-\frac{N_0\theta_l}{p_l d_l^{-\alpha}}]\frac{1}{1 + \frac{p_w {d_l'}^{-\alpha}}{p_l d_l^{-\alpha}}\theta_l} \quad (7)$$

The probability of $Pr(\gamma_l^2 > \theta_w), Pr(\gamma_l^3 > \theta_l)$ can also be derived in a similar way as $Pr(\gamma_l^1 > \theta_l)$. Therefore, the probability that UE can successfully decode interested signal under concurrent transmission of LAA and Wi-Fi is

$$p_{sl} = Pr(\gamma_l^1 > \theta_l) + Pr(\gamma_l^1 \leq \theta_l)Pr(\gamma_l^2 > \theta_w)Pr(\gamma_l^3 > \theta_l) \quad (8)$$

The successfully decoding probability of Wi-Fi STA can be obtained similarly.

B. *Cross-network Energy Detection Probability*

In our system model, We aim at optimizing the CCA thresholds so as to improve the sum of both networks' throughput by encouraging concurrent transmissions whenever possible. Since the cross-network energy detection probability impacts the throughput, we need to calculate the imperfect cross-network energy detection probability of LAA and Wi-Fi as a function of CCA thresholds.

Assume a Wi-Fi transmission is active in the LAA/Wi-Fi coexistence scenario, the CCA threshold of LAA BS is C_l. To access the shared channel, LAA BS needs to measure its sensed energy and compare it with C_l, LAA BS can only access the channel when its measured energy is below C_l. In LAA BS side, the sensed energy is

$$E_l = P_w|h_{wl}|^2, \quad (9)$$

Where h_{wl} is the channel between Wi-Fi AP and LAA BS. According to Rayleigh channel model, E_l is exponentially distributed, hence, the detection probability of Wi-Fi transmissions in LAA BS is

$$p_{dl} = Pr(E_l > C_l) = \exp[-\frac{C_l}{P_w d_{wl}^{\alpha}}], \quad (10)$$

where d_{wl} is the distance between LAA BS and Wi-Fi AP. We can see from Eq. (10), the cross-network detection probability is exponentially decreasing as CCA threshold.

V. THEORETICAL ANALYSIS OF LAA/WI-FI COEXISTENCE

In this section, we give theoretical analysis for LAA/Wi-Fi coexistence with saturated traffic. Several papers [7]–[9] analyze the LAA/Wi-Fi coexistence according to Bianchi's Markov model [6]. However, all of them assume Wi-Fi/LAA nodes are located in a dense environment, with no hidden terminals and capture effect. The closest work to ours is [10]. Although it investigated the impact of energy detection to LAA/Wi-Fi coexistence, it does not allow concurrent transmissions to improve the throughput of LAA/Wi-Fi, concurrent transmissions always lead to packet collision. Furthermore, it does not consider interference cancellation techniques. Hence the total channel utilization for LAA/Wi-Fi coexistence network does not exceed 1. Our work allows for concurrent transmissions and aims to derive the optimal CCA threshold that enables as many simultaneous transmissions between coexisting LTE and Wi-Fi as possible. Besides, we propose to exploit successive interference cancellation to further increase the chance of concurrent transmissions. Specifically, we study how to integrate energy detection, concurrent transmissions and interference cancellation into the Markov model and derive throughput expressions even under concurrent transmissions. The key challenges of theoretical analysis in our work are: (1) The energy detection threshold impacts the packet collision probability, but also affects the channel access probability of both networks and channel occupation/busy probability. Some previous works [9] used a 3-D Markov model which are more accurate for perfect detection, but the above probabilities are more difficult to compute. (2) The transmit durations of LAA and Wi-Fi are different, which means LAA and Wi-Fi can start contending/transmitting at any time, resulting in many possible overlapping transmission events. This makes it difficult to obtain the expected duration of all possible events, which is key to calculate the throughput.

We solve the above challenges by adopting a 2-D Markov model which abstracts out some details of the protocol, while making some approximations when computing the collision probabilities and the interval between two consecutive transmissions. These approximations make the problem tractable, while incurring an acceptable trade-off in the accuracy of the model as we will show later.

A. Analysis of Channel Access Probabilities based on Markov Model

Analysis for Wi-Fi. The Markov chain model of Wi-Fi systems is shown in Fig. 4 [6]. Denote each state as $\{s(t), b(t)\}$, where $s(t)$ is the transmission stage in time t, and $b(t)$ is the back-off counter in t. The conditional collision probability of Wi-Fi node is denoted as p_{cw}. A Wi-Fi node can only transmit when its back-off counter reaches 0 for each transmit stage. If the Wi-Fi transmission collides with other transmissions, the contention window is doubled up to the maximum contention window. When the transmission stage j satisfies $W_{max} = 2^j W_{min}$, the Wi-Fi node can transmit one more attempt while keeping the maximum contention window. After that, the Wi-Fi node will set its contention window to W_{win} no matter whether the last re-transmission is successful or not.

Consider the probability that Wi-Fi AP transmits in any time slot, a.k.a. channel access probability (τ_w). According to the transition probabilities among states and the fact that the summation of stationary probabilities of states is equal to 1, we can obtain τ_w as a function of p_{cw} [10]:

$$\tau_w = \frac{2}{W_{min}\left(\frac{(1-(2p_{cw})^{m+1})(1-p_{cw})+2^m(p_{cw}^{m+1}-p_{cw}^{m+2})(1-2p_{cw})}{(1-2p_{cw})(1-p_{cw}^{m+2})}\right)+1} \tag{11}$$

where $m = \log_2(\frac{W_{max}}{W_{min}})$.

Note that, different from other papers [7]–[10], we incorporate the impact of energy detection on concurrent transmission which further influences the conditional collision probability, since Wi-Fi collides with LAA only if LAA concurrently transmits with it and Wi-Fi receiver cannot decode its signal of interest. Therefore, we will derive p_{cw} as a function of $\tau_l, p_{dw}, p_{dl}, p_{sw}$ in Section V-B.

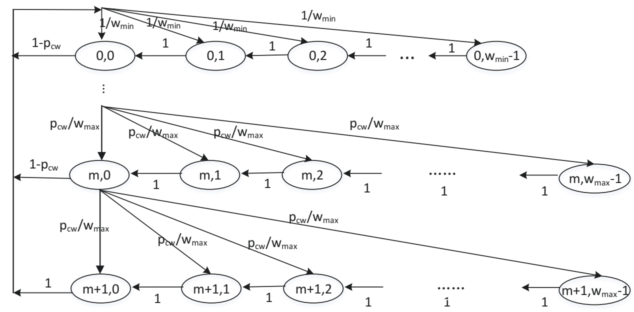


Fig. 4: The Markov model for Wi-Fi (the same for LAA with different parameters).

Analysis for LAA. The Markov model of LAA networks and analysis is similar to Fig. 4, where we denote the minimum contention window of LAA as W'_{min}, the probability that LAA BS transmits in a time slot as τ_l, the conditional collision probability of LAA as p_{cl}, following same derivation process as Wi-Fi, τ_l can be obtained as [10]:

$$\tau_l = \frac{2}{W'_{min}\left(\frac{(1-p_{cl})(1-(2p_{cl})^{m'+1})}{(1-2p_{cl})(1-p_{cl}^{m'+2})} + 2^{m'}\frac{p_{cl}^{m'+1}-p_{cl}^{m'+2}}{1-p_{cl}^{m'+2}}\right)+1} \tag{12}$$

where $m' = \log_2(\frac{W'_{max}}{W'_{min}})$.

Similarly, the probability of concurrent transmission for LAA and Wi-Fi is related to Wi-Fi's channel access probability τ_w and energy detection probability p_{dw}, p_{dl}, and the probability p_{sl} that LAA successfully decodes interested signal under concurrent transmission, which will be derived in Section V-B.

B. Conditional Collision Probability Analysis for LAA/Wi-Fi

We analyze the LAA/Wi-Fi coexistence based on Markov model. As presented in Section V-A, we have obtained two equations (Eqs. (11) and (12)) with four unknown variables $\tau_w, \tau_l, p_{cw}, p_{cl}$. Eq. (11) shows that τ_w is related to p_{cw}, Eq. (12) shows that τ_l is related to p_{cl}. To obtain solutions for $\tau_w, \tau_l, p_{cw}, p_{cl}$, we need to obtain two more equations. Namely, we need to derive the function of p_{cw}, p_{cl} w.r.t. τ_w or τ_l, considering the energy detection probability and successfully decoding probability.

Traditionally, if there is no hidden terminal, we can easily obtain the relationship between conditional collision probabilities and channel access probabilities. That is, the conditional collision probability of Wi-Fi is equal to the channel access probability of LAA, and likewise for the LAA network. However, under imperfect energy detection of LAA and Wi-Fi networks, these calculations should be modified. Firstly, We define three events (denoted as E_1, E_2, E_3 in table II) which lead to concurrent transmissions of LAA and Wi-Fi.

The above three events are also shown in Fig. 5. Fig. 5 (a) shows E_1 which is Wi-Fi accesses the channel at the same time with LAA, e.g. t_0; Fig. 5 (b) shows E_2, where LAA first accesses channel at t_0. However Wi-Fi does not hear the

TABLE II: Three events of concurrent transmission of LAA and Wi-Fi.

Event	Definition
E_1	Wi-Fi and LAA access the channel at the same time
E_2	LAA accesses channel first but Wi-Fi does not hear LAA
E_3	Wi-Fi accesses channel first but LAA does not hear Wi-Fi

ongoing LAA transmission and accesses the channel at a later time t_1 which is within the TXOP of LAA (since the back-off stage duration is much smaller than the TXOP); Fig. 5 (c) shows E_3, where Wi-Fi accesses the channel first at t_0; however, LAA does not hear the ongoing Wi-Fi transmission and accesses the channel at t_1.

Then we show how to calculate the conditional collision probability of LAA. Suppose that LAA accesses the channel at t_0. According to Fig. 5, there are three events that lead to concurrent transmissions of LAA and Wi-Fi. The first event is that Wi-Fi also accesses channel at t_0, which is the same as Fig. 5 (a). This happens with probability τ_w. The second event is that Wi-Fi does not access the channel at t_0 but cannot hear LAA's transmission hence accesses channel later. This event happens with probability $(1-\tau_w)(1-p_{dw})$. The third event is that Wi-Fi accesses the channel before t_0, however, LAA does not hear the Wi-Fi transmission and access channel at t_0. Since we cannot estimate whether Wi-Fi accesses channel in previous slots with the 2-D Markov model, we ignore the third event when calculating the conditional collision probability of LAA. Based on the above analysis, given that LAA accesses the channel in time slot t_0, the conditional probability of overlapping transmissions for LAA and WiFi is approximately calculated as $\tau_w + (1-\tau_w)(1-p_{dw})$.

With SIC capability, even under the concurrent transmission of LAA and Wi-Fi, LAA UE may still be able to successfully decode its interested signal. Denote the successful decoding probabilities of LAA and Wi-Fi as p_{sl}, p_{sw}, respectively. For an LAA receiver, a packet collision implies two events: overlapping transmission between LAA and Wi-Fi, and also LAA UE fails to decode the signal transmitted by LAA BS. Therefore, the conditional collision probability of LAA is:

$$p_{cl} = [\tau_w + (1-\tau_w)(1-p_{dw})](1-p_{sl}) \tag{13}$$

Similarly, the conditional collision probability of Wi-Fi is

$$p_{cw} = [\tau_l + (1-\tau_l)(1-p_{dl})](1-p_{sw}) \tag{14}$$

Until now, we have obtained four Eqs. (11), (12), (13), (14) with four unknown variables $\tau_w, \tau_l, p_{cw}, p_{cl}$. We can jointly solve these equations to obtain the numerical results.

C. Normalized Throughput of Coexisting LAA/Wi-Fi Links

The normalized throughput of LAA (Wi-Fi) is defined as the ratio of time occupied by the successful LAA (Wi-Fi) transmissions to the interval between two consecutive LAA (Wi-Fi) transmissions [20]. Thus, we need to measure the interval between two consecutive LAA (Wi-Fi) transmissions. In previous works, since there are no partially overlapping cases for LAA/Wi-Fi coexistence, we can easily obtain the interval between two consecutive transmissions. However, in our work, the nature of partially overlapping transmissions for LAA and Wi-Fi due to imperfect cross-network detection brings new challenges to calculate it. We divide all the transmissions into three cases. Denote $t_l = TXOP_l, t_w = TXOP_w$.

1) LAA Transmits Alone: According to Fig.5 (a), to guarantee the exclusive transmission of LAA, the Wi-Fi counter should not hit zero at time slot t_0 and the Wi-Fi AP should be able to detect the transmission of the ongoing LAA transmission after t_0. This event happens with probability $\tau_l(1-\tau_w)p_{dw}$, and the duration of this event is t_l.

2) Wi-Fi Transmits Alone: To ensure the exclusive transmission of the Wi-Fi network, at the time slot Wi-Fi accesses the channel, LAA counter should be greater than 0 and LAA BS should be to able to detect the ongoing Wi-Fi transmission. Hence, the probability that Wi-Fi transmits alone is $\tau_w(1-\tau_l)p_{dl}$, the duration of this event is t_w.

3) Concurrent Transmission of LAA and Wi-Fi: As we have discussed in Section V-B, there are three events that lead to concurrent transmissions of LAA and Wi-Fi. We discuss the probabilities of these events first.

For E_1, since both LAA and Wi-Fi access channel at the same time, the probability of E_1 is easily calculated as

$$Pr(E_1) = \tau_l \tau_w. \tag{15}$$

For E_2 (shown in Fig. 5 (b)), the probability that LAA accesses channel at t_0 while Wi-Fi does not access at the same time is $\tau_l(1-\tau_w)$. Based on this, Wi-Fi does not hear the ongoing LAA transmission with probability $1-p_{dw}$, hence the probability of E_2 is obtained as

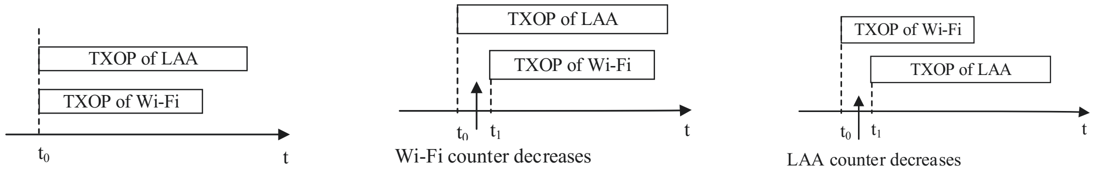
$$Pr(E_2) = \tau_l(1-\tau_w)(1-p_{dw}). \tag{16}$$

For E_3 (shown in Fig. 5 (c)), we can easily obtain the probability of E_3 following the similar analysis as E_2:

$$Pr(E_3) = \tau_w(1-\tau_l)(1-p_{dl}). \tag{17}$$

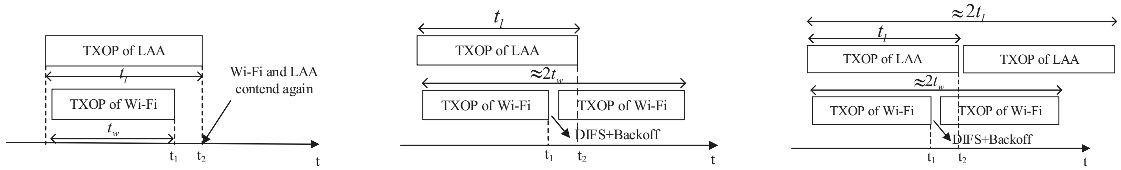
Therefore, the probability of concurrent transmissions of LAA and Wi-Fi is $Pr(E_1) + Pr(E_2) + Pr(E_3) = p_{sim}$.

Next, we need to obtain the average duration of events E_1, E_2, E_3 for LAA and Wi-Fi respectively. To be consistent with 3GPP and Wi-Fi standards, we consider the TXOP parameters shown in Table I. Regardless of event E_1, E_2 or E_3, since the TXOP of LAA is larger than that of Wi-Fi, after the first TXOP of Wi-Fi finished, the Wi-Fi AP still needs to sense the channel availability before it starts next TXOP. There are many overlapping scenarios depending on how many LAA or Wi-Fi packets overlap. For simplicity, we only show three scenarios in Fig. 6, assuming LAA accesses the channel first (E_2). As shown in Fig. 6 (a), the first TXOP of Wi-Fi is ended at t_1, thus Wi-Fi needs to sense the channel before it starts next TXOP. There is probability p_{dw} for Wi-Fi to detect the ongoing LAA transmission at t_1, if this happens, Wi-Fi would back-off until t_2 and contend with LAA again for channel access, therefore the duration of events E_1, E_2, E_3 for Wi-Fi is t_l, with probability p_{dw}; In Fig. 6 (b), we show that, at time t_1, there is probability $1-p_{dw}$ that Wi-Fi does not sense the ongoing LAA transmission, hence Wi-Fi will start a new Wi-Fi transmission after DIFS plus random back-off, the duration of events E_1, E_2, E_3 for Wi-Fi is approximately $\frac{2t_w}{2} = t_w$,



(a) (b) (c)

Fig. 5: Concurrent transmissions of LAA and Wi-Fi: (a) E_1: LAA and Wi-Fi access the channel at the same time; (b) E_2: LAA accesses channel first but Wi-Fi cannot hear LAA; (c) E_3: Wi-Fi accesses channel first but LAA does not hear Wi-Fi.



(a) (b) (c)

Fig. 6: (a) At t_1, Wi-Fi can sense the ongoing LAA transmission with probability p_{dw}; (b) At t_1, Wi-Fi cannot sense the ongoing LAA transmission with probability $1-p_{dw}$; (c) At t_1, Wi-Fi does not sense the ongoing LAA transmission, and at t_2, LAA does not sense the ongoing Wi-Fi transmission.

with probability $1-p_{dw}$. Therefore, the average duration of events E_1, E_2, E_3 for Wi-Fi system is approximately

$$t_{cw} = p_{dw}t_l + (1-p_{dw})t_w. \tag{18}$$

Following the same process, we can obtain the average duration of events E_1, E_2, E_3 for LAA network. As shown in Fig. 6 (a), if Wi-Fi senses the LAA transmission at t_1, the duration of events E_1, E_2, E_3 for LAA is t_l, with probability p_{dw}. However, if Wi-Fi does not sense the LAA transmission at t_1, as shown in Fig. 6 (b), at t_2, LAA needs to sense the Wi-Fi transmission. There are two outcomes depending on whether LAA could sense the ongoing Wi-Fi transmission or not. If LAA can sense the second TXOP of Wi-Fi, the duration of events E_1, E_2, E_3 for LAA is $2t_w$ (shown in Fig. 6 (b)), with probability p_{dl}; if LAA BS does not sense the ongoing Wi-Fi transmission, the duration for LAA is approximately $\frac{2t_l}{2} = t_l$ (because back-off duration is much smaller than TXOP, shown in Fig. 6 (c)), with probability $1-p_{dl}$. Due to unlimited number of overlapping cases of LAA and Wi-Fi especially when p_{dw}, p_{dl} are close to 0, we cannot exhaust all of them. Thus, we only consider several most likely overlapping cases of LAA and Wi-Fi as shown in Eqs. (18)(19). The probabilities of other overlapping cases decreases as the number of overlapping TXOPs increases. From the results shown in section VI, the approximation is acceptable, compared with simulations. The average duration of events E_1, E_2, E_3 for LAA is approximately

$$t_{cl} = p_{dw}t_l + (1-p_{dw})[2t_w p_{dl} + t_l(1-p_{dl})]. \tag{19}$$

Considering all the events analyzed above (LAA transmits alone, Wi-Fi transmits alone, concurrent transmission of LAA and Wi-Fi, idle), the average interval of two consecutive Wi-Fi transmissions is

$$\begin{aligned} t_{ew} = {} & (1-\tau_w)(1-\tau_l)\sigma + \tau_w(1-\tau_l)p_{dl}t_w \\ & + \tau_l(1-\tau_w)p_{dw}t_l + p_{sim}t_{cw}. \end{aligned} \tag{20}$$

The average interval of two consecutive LAA transmissions is obtained as

$$\begin{aligned} t_{el} = {} & (1-\tau_w)(1-\tau_l)\sigma + \tau_w(1-\tau_l)p_{dl}t_w \\ & + \tau_l(1-\tau_w)p_{dw}t_l + p_{sim}t_{cl}. \end{aligned} \tag{21}$$

The occupied time of successful Wi-Fi transmission within the interval of two consecutive Wi-Fi transmission includes the time that Wi-Fi transmits alone and that Wi-Fi transmits under concurrent transmissions with LAA. Let p_{sw}, p_{sl} represent the probability of successful decoding for Wi-Fi and LAA network under concurrent transmission. According to the definition of normalized throughput, the normalized throughput of Wi-Fi is calculated as

$$thr_w = \frac{\tau_w(1-\tau_l)p_{dl}t_w + p_{sw}t_w p_{sim}}{t_{ew}} \tag{22}$$

Similarly, the normalized throughput of LAA is calculated as

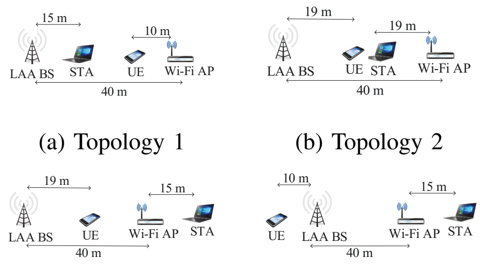
$$thr_l = \frac{\tau_l(1-\tau_w)p_{dw}t_l + p_{sl}t_l p_{sim}}{t_{el}} \tag{23}$$

D. Average Normalized Throughput of LAA and Wi-Fi

From Eqs. (22) and (23), we know the throughput of Wi-Fi and LAA is related to $p_{dw}, p_{dl}, p_{sw}, p_{sl}$, which is further determined by LAA/Wi-Fi coexistence topology. Assuming random scheduling, down-link transmission to UE i and STA j in LAA or Wi-Fi network has equal probability. The throughput of the link from BS to UE i when it coexists with link from AP to STA j is denoted as $thr_l^i(i,j)$, the throughput of STA j when it coexists with UE i is denoted $thr_w^j(i,j)$. We can compute $thr_l^i(i,j), thr_w^j(i,j)$ from Eqs. (22) and (23). Suppose there are M users in the LAA network and N users in Wi-Fi network, the average normalized throughput of LAA and Wi-Fi networks can be expressed as:

$$\bar{thr_l} = \frac{\sum_{i=1}^{M}\sum_{j=1}^{N} thr_l^i(i,j)}{MN} \tag{24}$$

$$\bar{thr_w} = \frac{\sum_{i=1}^{M}\sum_{j=1}^{N} thr_w^j(i,j)}{MN} \tag{25}$$



(a) Topology 1 (b) Topology 2 (c) Topology 3 (d) Topology 4

Fig. 7: LAA/Wi-Fi coexistence topology in our case study.

VI. Simulation Results

A. Simulation Setup

We conduct discrete-event simulation through MATLAB to validate our theoretical results. Both LAA and Wi-Fi networks have saturated traffic. LAA BS and Wi-Fi AP start contending channel access at 0ms and each simulation is run 10^6ms. We implement the Wi-Fi CSMA protocol and LAA's LBT according to the standards, except that the CCA thresholds can be varied. We adopt the Rayleigh channel model, the I/Q component of small scale fading follow the Gaussian distribution.

We create two sets of simulation scenarios. At first, for case study we adopt four typical scenarios in Fig. 7 to study the impact of various LAA/Wi-Fi coexistence topology on the throughput. Both LAA and Wi-Fi has a single downlink. In another simulation, to study the average effect, we put $N = 50$ STAs and $M = 50$ UEs randomly distributed in a square area (40×40 meters). Random scheduling is assumed for BS/AP to transmit to a single UE/STA at a time (picked with uniform probability). In all the above settings, the distance between LAA BS and Wi-Fi AP is always set to 40 meters, while the STA and UE positions vary. The channel access parameters of LAA and Wi-Fi (priority class I both for LAA and Wi-Fi) are shown in table I, other simulation parameters are listed in table III (similar parameters have been adopted in [2], [9]).

TABLE III: Simulation parameters

P_w	P_l	N_0	α	θ_l	θ_w
23 dBm	23dBm	-90 dBm	4	10 dB	10 dB

B. Simulation vs. Theoretical Analysis

First, we compare theoretical throughput analysis with simulation. For illustration, we only present both theoretical throughput and simulation results for topology 1, since others have similar relations. In Fig. 8 (a), we show the normalized throughput of Wi-Fi under different CCA thresholds of LAA and Wi-Fi. For a fixed CCA_l, increasing CCA_w enables more aggressive concurrent transmissions by Wi-Fi AP. Even under the condition that LAA BS accesses channel first, since Wi-Fi may not hear the ongoing transmission of LAA, Wi-Fi gains more opportunity to transmit. At the receiving STA, since the RSS of interested signal and interference signal are quite different, Wi-Fi STA still has a high probability to decode its signal using SIC. Therefore, The normalized throughput of Wi-Fi is improved when increasing CCA_w while fixing CCA_l. However, if we fix CCA_w and increase CCA_l, LAA will gain more transmission opportunity which increases the back-off probability of Wi-Fi. Hence, the normalized throughput of Wi-Fi is impaired. The similar trend is also applicable to LAA's throughput. Both simulation and analytical results show the same trend and for most parameter ranges they are very close to each other.

Note that, in Fig. 8 (a), (b), there is some mismatch between theoretical and simulation results, especially when CCA_w is large. This is because, the calculations of conditional collision probability (i.e., Eqs. (13), (14)) and expected duration between consecutive Wi-Fi/LTE transmissions (Eqs. (20) and (21)) are approximated. For lower energy detection probabilities, concurrent transmissions happen more frequently, which leads to more Wi-Fi and LAA packets overlapping together that affects the accuracy of Eqs. (13), (14).

C. Throughput vs. Topology, and Impact of SIC

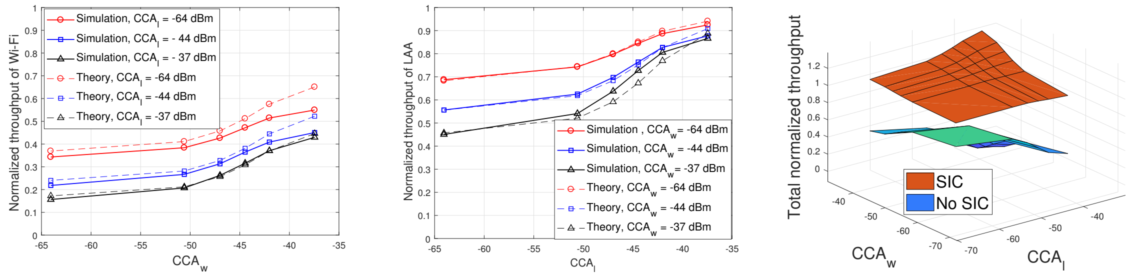
The normalized throughput of LAA and Wi-Fi for the other three topologies have similar trends as in Fig. 8 w.r.t. unilaterally increasing CCA_l (CCA_w), as it enables more concurrent transmissions which leads to improved throughput of LAA (Wi-Fi). Thus we omit their figures here and only present simulation results since theoretical results are close.

However, this may (or may not) come at a cost of decreasing the other network's throughput. Depending on the concrete topology, the CCA threshold pairs that maximize the total normalized throughput for both networks are different. For topology 1, as shown in Fig. 8 (c), without SIC, the optimal CCA threshold pair should satisfy $p_{dl} = p_{dw} = 1$ so as to avoid interference since both receivers are closer to their interference sources. However, with SIC, since the RSS of interested signal and interference signal received at either UE or STA are disparate, they can both decode own signals, thus the optimal CCA threshold pair will satisfy $p_{dl} = p_{dw} = 0$.

For topology 2, as shown in Fig. 9 (a), SIC does not improve the total throughput much, since UE (or STA) has similar distances to LAA BS and Wi-Fi AP – the interested signal's and interference signal's strengths are similar and would not benefit from SIC. Furthermore, the optimum CCA threshold pairs for both SIC or no SIC satisfy $p_{dl} = p_{dw} = 1$, meaning it's better to avoid interference in this case.

For topology 3, from Fig. 9 (b), the optimal CCA threshold pairs for both SIC and no-SIC satisfy $p_{dl} = p_{dw} = 0$. Since the RSSs of interested/interference signals at STA are disparate, it leads to Wi-Fi choose a high CCA_w in order to maximize Wi-Fi throughput; meanwhile, although the successful decoding probability of LAA is low, it is still beneficial for it to transmit simultaneously rather than being silent (without affecting Wi-Fi much). Therefore, the optimal CCA threshold pair for topology 3 should be high for both (satisfying $p_{dl} = p_{dw} = 0$).

For topology 4, as shown in Fig. 9 (c), the case with SIC has similar throughput as no-SIC since the interested signal is much stronger than interference for both UE and



(a) (b) (c)

Fig. 8: (a) The normalized throughput of Wi-Fi in topology 1; (b) The normalized throughput of LAA in topology 1; (c) The total normalized throughput, topology 1.

STA. This also causes Wi-Fi and LAA to both choose high CCA thresholds to maximize their own normalized throughput ($p_{dw} = 0, p_{dl} = 0$), which also maximizes the total.

D. The Average Case

We investigate the average normalized throughput for LAA/Wi-Fi, the detailed simulation parameters are described in the setup. We compute an average of the individual normalized throughput of all users in Wi-Fi and LAA network respectively, as shown in Eqs. (24) and (25). The average normalized throughput of Wi-Fi and LAA network is shown in Fig. 10. We can see that, concurrent transmissions combined with SIC can greatly improve the total average normalized throughput compared with default CCA threshold settings. This shows that on average, encouraging concurrent transmissions is beneficial to the coexistence performance overall.

VII. Practical Issues

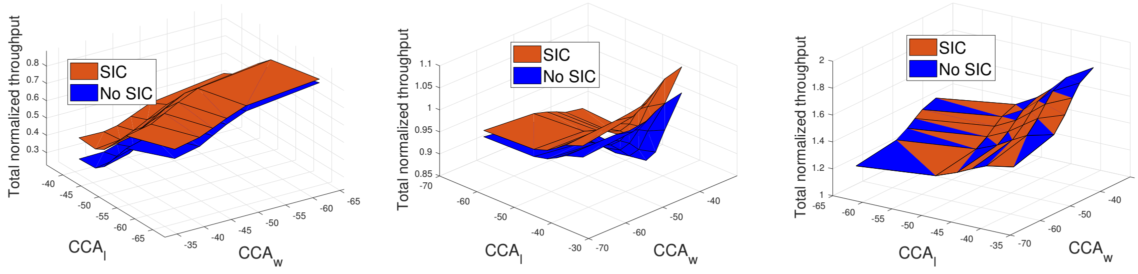
In this section, we discuss the challenges and possible ways to implement our framework in practice. In our throughput analysis, we assumed that the network topology/channel statistics are known in order to compute the successful decoding probabilities. However, it will be impractical to obtain global topology information about both networks and exchange it with every LAA/Wi-Fi node, due to the potential high communication overhead. Moreover, LAA and Wi-Fi have different PHY layers which makes it difficult for them to directly communicate with each other. Ideally, we need to avoid cross-technology communication (CTC) and make as little change to the protocol stack as possible.

Here we argue that it is possible to obtain the optimal (or near-optimal) CCA thresholds that maximize the total throughput, using only local information by implicit observation at each node (without explicit CTC). Initially, every node can set its CCA threshold to default low values (-72 dBm for LAA and -62 dBm for Wi-Fi). Each node can monitor the radio environment to measure the received signal strength (RSS) from all other nodes, and create a statistical profile (RSS distribution) for each transmitter (including its own intended transmitter). To identify an interferer's frames, we can use signal-correlation based methods [16], [21] without decoding them (since the preamble embeds the transmitter ID and contains repeated patterns). After that, each node i can compute the probability of successful decoding p_{si} under SIC, for each potential interferer. If p_{si} is close to 1, it will inform its own transmitter to set the CCA threshold to a high value ($p_d \to 0$); otherwise, p_{si} is close to 0, the CCA threshold will remain as default ($p_d \to 1$). We can see that this strategy is optimal when the topology is symmetric (Topologies 1, 2, and 4 in Fig. 7). To apply to asymmetric topologies (e.g., Fig. 7 (c)), UE and STA can infer it from the interference result (Wi-Fi AP will transmit while LAA BS does not), then they can adjust their CCA thresholds according to optimal ones in this case (both set to high values). Note that, changing CCA thresholds itself does not change existing Wi-Fi/LAA protocols, which is also backward-compatible.

The other question is how to realize SIC across the two networks. To enable this, a node needs to obtain the channel state information of a cross-technology link, and be able to reconstruct its signal (if stronger) to cancel it out. Previous work [17] designed wizBee for Wi-Fi/ZigBee coexistence using SIC, with an interference management block for Wi-Fi interference detection, estimation and cancellation. Since Wi-Fi and LAA have similar PHY protocol structure (they both use OFDM and span similar frequency ranges), we argue that with little modifications to the protocol (such as preloading Wi-Fi node with LAA's preamble information), a similar approach can be adopted in Wi-Fi/LAA networks. Note that, if nodes are equipped with multiple antennas, we can also use MIMO-based interference cancellation techniques such as [14], [18].

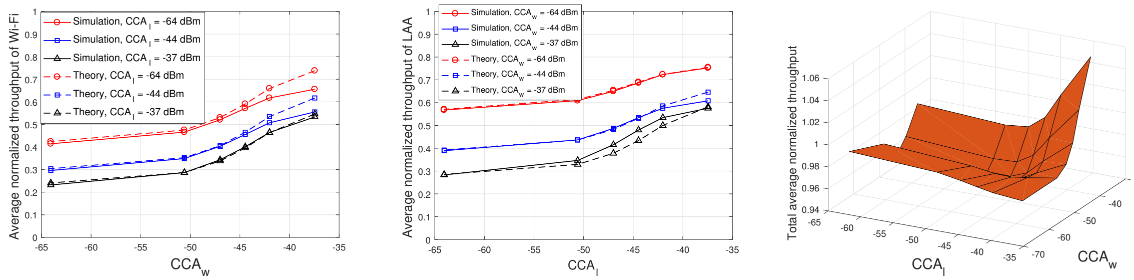
VIII. Conclusion

In this paper, we propose to enable concurrent transmissions of LAA and Wi-Fi by adjusting CCA thresholds, and combine interference cancellation techniques to improve overall throughput. We adopt a Markov-model based approach to quantify both networks' throughput with imperfect energy detection and SIC, from which the optimal CCA threshold pairs can be derived. Simulations results under four typical coexistence topologies showed that in many scenarios, significant improvements on total throughput are gained using optimal CCA thresholds, compared with the default CCA setting that avoids interference. Simulation results also validate our theoretical analysis. So far we consider two-link coexistence at any



(a) (b) (c)

Fig. 9: (a) Total normalized throughput of topology 2; (b) Total normalized throughput of topology 3; (c) Total normalized throughput of topology 4. The curves of SIC and No-SIC are very close to each other.



(a) (b) (c)

Fig. 10: (a) The average normalized throughput of Wi-Fi; (b) The average normalized throughput of LAA; (c) Total average normalized throughput of LAA/Wi-Fi coexistence.

given time. As future work, we will extend the Markov model to handle multiple coexisting links with interference cancellation capabilities, where each link's concurrent transmission decision depends on which link transmits before it. The optimal transmission strategies will be analyzed. Moreover, we will consider the case of non-cooperative networks using game-theoretic analysis, as well as real-world implementation. Interestingly, although each network can improve its own throughput by unilaterally increasing its own CCA threshold, it may not result in maximum overall throughput.

REFERENCES

[1] F. C. Commission, "FCC part 15 ruling: Radio frequency devices," Feb. 2013.

[2] "IEEE standard for information technology telecommunications and information exchange between systems local and metropolitan area networksspecific requirements - part 11: Wireless lan medium access control (MAC) and physical layer (PHY) specifications," *IEEE Std 802.11-2016 (Revision of IEEE Std 802.11-2012)*, pp. 1–3534, Dec 2016.

[3] "Qualcomm whitepaper: Extending lte advanced to unlicensed spectrum," https://www.qualcomm.com/media/documents/files/white-paper-extending-lte-advanced-to-unlicensed-spectrum.pdf, 2013.

[4] 3GPP, "Physical layer procedures," *3GPP TR 36.213 v13.4*,, Dec. 2016.

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

[6] G. Bianchi, "Performance analysis of the ieee 802.11 distributed coordination function," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 535–547, March 2000.

[7] Y. Gao, X. Chu, and J. Zhang, "Performance analysis of laa and wifi coexistence in unlicensed spectrum based on markov chain," in *2016 IEEE Global Communications Conference (GLOBECOM)*, Dec 2016, pp. 1–6.

[8] A. M. Baswade, L. Beltramelli, F. A. Antony, M. Gidlund, B. R. Tamma, and L. Guntupalli, "Modelling and analysis of wi-fi and laa coexistence with priority classes," in *2018 14th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, Oct 2018, pp. 1–8.

[9] M. Hirzallah, Y. Xiao, and M. Krunz, "On modeling and optimizing lte/wi-fi coexistence with prioritized traffic classes," in *2018 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, Oct 2018, pp. 1–10.

[10] M. Mehrnoush, V. Sathya, S. Roy, and M. Ghosh, "Analytical modeling of wi-fi and lte-laa coexistence: Throughput and impact of energy detection threshold," *IEEE/ACM Transactions on Networking*, vol. 26, no. 4, pp. 1990–2003, Aug 2018.

[11] R. Yin, G. Yu, A. Maaref, and G. Y. Li, "Lbt-based adaptive channel access for lte-u systems," *IEEE Transactions on Wireless Communications*, vol. 15, no. 10, pp. 6585–6597, Oct 2016.

[12] G. J. Sutton, R. P. Liu, and Y. J. Guo, "Delay and reliability of load-based listen-before-talk in laa," *IEEE Access*, vol. 6, pp. 6171–6182, 2018.

[13] Y. Xiao, M. Hirzallah, and M. Krunz, "Distributed resource allocation for network slicing over licensed and unlicensed bands," *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 10, pp. 2260–2274, Oct 2018.

[14] S. Gollakota, F. Adib, D. Katabi, and S. Seshan, "Clearing the rf smog: making 802.11 n robust to cross-technology interference," in *ACM SIGCOMM*, vol. 41, no. 4. ACM, 2011, pp. 170–181.

[15] Y. Hou, M. Li, X. Yuan, Y. T. Hou, and W. Lou, "Cooperative cross-technology interference mitigation for heterogeneous multi-hop networks," in *IEEE INFOCOM 2014-IEEE Conference on Computer Communications*. IEEE, 2014, pp. 880–888.

[16] P. Yang, Y. Yan, X. Li, Y. Zhang, Y. Tao, and L. You, "Taming cross-technology interference for wi-fi and zigbee coexistence networks," *IEEE Transactions on Mobile Computing*, vol. 15, no. 4, pp. 1009–1021, April 2016.

[17] Y. Yan, P. Yang, X. Li, Y. Zhang, J. Lu, L. You, J. Wang, J. Han, and Y. Xiong, "Wizbee: Wise zigbee coexistence via interference cancellation with single antenna," *IEEE Transactions on Mobile Computing*, vol. 14, no. 12, pp. 2590–2603, Dec 2015.

[18] S. Yun and L. Qiu, "Supporting wifi and lte co-existence," in *2015 IEEE Conference on Computer Communications (INFOCOM)*, April 2015, pp. 810–818.

[19] S. Verdu *et al.*, *Multiuser detection*. Cambridge university press, 1998.

[20] Zhen-ning Kong, D. H. K. Tsang, B. Bensaou, and Deyun Gao, "Performance analysis of ieee 802.11e contention-based channel access," *IEEE Journal on Selected Areas in Communications*, vol. 22, no. 10, pp. 2095–2106, Dec 2004.

[21] I. Samy, L. Lazos, Y. Xiao, M. Li, and M. Krunz, "Lte misbehavior detection in wi-fi/lte coexistence under the laa-lte standard," in *Proceedings of the 11th ACM Conference on Security & Privacy in Wireless and Mobile Networks*, ser. WiSec '18. ACM, 2018, pp. 87–98.