Analysis of Generalized CCA Errors and Mitigation in LTE-LAA Spectrum Sharing System

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Abstract— **Carrier sense multiple access with collision avoidance (CSMA/CA) procedures have been specified for medium access control (MAC) in several incumbent and emerging wireless systems, such as wireless local area network (WLAN) and long-term evolution (LTE) with license assisted access (LAA). Clear channel assessment (CCA) errors in carrier sensing can cause significantly degraded network performance. Analyzing the impact of CCA errors in the MAC backoff and transmission process is a challenging task, and very few works have explicitly addressed this. Existing analytical work is only valid for special cases such as independent CCA errors, and the result lacks generality for extension to coexistence systems. In this paper, we try to fill this technical gap by modelling generalized CCA sensing errors which can be either fully correlated or independent due to the fading channel. We develop a new Markov model using matrix-vector representation which captures generalized CCA error events, and analyze the impact of CCA errors on the key performance indicators (KPIs), such as the throughput of both LTE-LAA and WLAN systems. To mitigate the effects of mis-detection and collisions which can cause the network throughput to drop to nearly zero, we propose a soft-collision method to reduce the performance loss. Finally, we program the LTE-LAA and WLAN CCA algorithms and implement extensive computer simulations. Comparisons between analytical and simulation results show consistent matching, and illustrate loss caused by sensing errors and improvement brought by the soft-collision method. This result provides a powerful analytical tool on CSMA/CA MAC-layer performance evaluation with imperfect sensing, applicable to both single and coexistence systems, and has practical value for countermeasure designs against sensing errors.**

I. Introduction

In spectrum sharing systems, such as long-term evolution license assisted access (LTE-LAA) [1]–[5] and the IEEE 802.11 wireless local area network (WLAN) systems [6], [7], reliable spectrum sensing of channel busy/idle states is needed to properly implement carrier sense multiple access with collision avoidance (CSMA/CA) schemes. In CSMA/CA, the clear channel assessment (CCA) result is subject to false alarm and mis-detection events, which can cause either unwanted transmission delay or collisions, and significantly reduce the network throughput. Accurate evaluation of the impact of CCA errors and design of effective countermeasures are critical to improve network performance, and enable constructive coexistence.

The effects of sensing errors on wireless spectrum access systems have been studied in a few works, such as [8]–[11]. The authors of [8] have evaluated the effects of sensing errors on the performance of opportunistic spectrum access, assuming a constrained partially observable Markov decision process (POMDP). An IEEE 802.11-based cognitive radio scheme is proposed and analyzed in [9], and the impact of sensing errors of primary user activity on secondary transmissions is studied. In [10], the authors propose a throughput-optimal CSMA scheme to mitigate the impact of imperfect sensing, especially the mis-detection event. They use a retransmission probability instead of modelling backoff countdown process. The effect of CCA errors in the CSMA/CA backoff process is not explicitly modelled or studied in [8]–[10].

In [11], the authors model and analyze the effect of CCA errors on the medium access control (MAC) backoff countdown and transmission processes for a CSMA/CA network. However, this method has restrictions and major approximations. First, it assumes the special case of independent CCA errors among counter reduction (CR) steps, which may hold when the channel fading is very fast (aka, channel changes independently among backoff slot durations). This assumption is not valid for a slow fading (or blockwise fading) channel where the mis-detection events in multiple sensing slots on a transmission packet are highly correlated. Second, similar to available works [12], [13] of Markov chain-based CSMA/CA modelling, it uses a scalar-variable probability transition method to analyze system states, and cannot model generalized CCA errors. Third, some analytical steps in [11] involve approximations which are tight only for certain ranges of parameters.

In WLAN and LAA small-cell networks where the channel fading is not very fast, the CCA sensing output among backoff slots can be highly correlated, and therefore so are the CCA errors. We define generalized CCA errors to encompass both correlated and independent CCA errors in CSMA/CA backoff process. A flexible and precise modeling and analysis approach which can handle generalized CCA errors is still missing in the literature.

Recently, some analytical or optimization approaches for the LTE-LAA and WLAN coexistence systems have been developed assuming perfect spectrum sensing, see e.g., [14]–[18]. In these works, CCA errors were not modelled or analyzed. Evaluating impact of CCA errors on coexistence systems is a nontrivial task, and has not been well explored. Thus, we identify the following challenging open problems:

1) Analyzing effect of generalized CCA errors on CSMA/CA network performance (explicitly counting for

the backoff process).
2) Evaluating impact of generalized CCA errors on unlicensed spectrum sharing systems, such as coexisting LTE-LAA and WLAN.

In this paper, we model and address these challenging problems in a unified framework. The novel contributions are highlighted as follows:

- New model of backoff process assuming generalized CCA errors. Instead of the majority of available works which represent the CSMA/CA backoff in a scalar process, we develop a matrix-vector Markov tool to model generalized CCA errors, and compute the backoff counter stationary probability vector. To do this, we enumerate all the channel access and CCA sensing events, and provide in-depth and accurate performance analysis.
- We provide the result for two spectrum sharing CSMA/CA networks, aka. coexisting LAA and WLAN networks, and derive key performance indicators (KPIs), including the channel access probability (CAP), successful transmission probability (STP), and throughput.
- Direct retransmission of collided packets in LAA and WLAN is equivalent to a hard-collision model because the packets experiencing collisions are lost. To mitigate the performance loss, we also propose a soft-collision scheme. We program the MAC algorithms and implement extensive simulations, which validate our analytical results, and demonstrate the performance improvement of the soft-collision method.

This new technique fills a major gap in modelling and analysis of generalized CCA errors in CSMA/CA systems, with applications such as LTE-LAA and WLAN coexistence. The technical insight and method provided by this work may be used for analysis and optimization of other coexisting systems, and mitigate the impact of significant sensing errors.

II. System Model

Consider two spectrum sharing systems on an industrial, scientific, and medical (ISM) radio band, where there is an LTE-LAA system with n_L links and a WLAN system with n_W links. They share a single wide-band channel, and use CSMA/CA type of MAC channel access procedures specified in [1], [2], [6]. Suppose that with perfect CCA, every link can hear the channel access activity of any other links. With imperfect CCA, there are two types of sensing errors, false alarm on an idle slot and mis-detection of an ongoing transmission.

In this section, we use subscripts L, W, I, S, C, P to denote LAA, WLAN, idle, successful transmission, collision, and payload, respectively. We define the false alarm and mis-detection probabilities of the LAA (and WLAN) system as $P_{\text{Fa},L}$ and $P_{m,L}$ (and $P_{\text{Fa},W}$ and $P_{m,W}$), respectively. For the LAA (and WLAN) system, we define δ_L, $T_{P,L}$, $T_{S,L}$ and $T_{C,L}$ (and δ_W, $T_{P,W}$, $T_{S,W}$ and $T_{C,W}$) as the durations of the idle slot, payload, successful transmission, and collided transmission, respectively.

Assume that the background white noise power is negligible compared to the interference power. Based on a popular Jake's fading spectrum [19] for a time-selective Rayleigh fading channel, we obtain the channel power correlation between slots of n-slot separation as

$$\rho(n) \simeq |J_0(2\pi f_d n \delta_L)|^2 \tag{1}$$

where J_0 is the Bessel function of zeroth-order, f_d is maximum Doppler frequency shift, $\delta_L = 9\mu s$ is an idle slot duration. Based on pedestrian moving speed of 2 m/s at carrier frequency 5.2 GHz, we obtain $f_d \leq 34.67$ Hz, and $\rho(1) \simeq 1$, which means that adjacent CCA results are fully correlated. For two CCA results that are seperated by 1 ms, we have $n \simeq 111$, and $\rho(111) \simeq 0.977$, which is close to full correlation. Therefore, in LAA small cells and WLAN, during sensing of a transmission packet, the involved CCA errors are typically highly correlated. To our knowledge, this case has not been adequately analyzed in the literature. We will address this difficult and practical case, and our result can be applied to independent CCA errors as well (aka, fast fading channel).

Direct retransmission of collided packets can suffer substantially from CCA errors. Hybrid automatic repeat request (H-ARQ) has been discussed for adoption in 3GPP LTE-LAA [2] and new-radio (NR)-LAA [20] channel access procedures. With H-ARQ, receiver can combine several corrupted copies of the original packet and maintain partial throughput at a lower rate. By considering H-ARQ, we propose a CCA soft-collision (CCA-SC) scheme.

The CCA-SC scheme:

1) Initialize counter and starts backoff based on CSMA/CA. When the counter reduces to zero, transmit one packet.
2) If transmission is successful, receiver sends back ACK. The next packet is scheduled. Go to step 1).
3) If transmission fails:
   - Increase backoff stage, and another encoded copy of the failed packet is scheduled for retransmission. The receiver combines the corrupted copies to recover the original packet, and send ACK/NACK to the transmitter. Go to step 1).
   - Retransmission is stopped when either the packet is recovered correctly or the maximum retransmission count is exceeded.

For ease of reference, some symbols, expressions and their definitions are listed in Table I.

III. Performance Analysis

A. Throughput Under CCA Errors and Hard-Collision

We use H_0 and H_1 to denote that the channel are truly idle and busy, respectively. We define τ_{L,H_0} and τ_{L,H_1} (and τ_{W,H_0} and τ_{W,H_1}) as channel access probabilities of an LAA (and WLAN) link under H_0 and H_1 states. Let Z_0 and W_0 be the initial contention window (CW) sizes of LAA and WLAN systems, respectively. For LAA (and WLAN) system, we define P_{I,L,H_0}, P_{I,L,H_1}, P_{S,L,H_0}, and $P_{C,L}$ (and P_{I,W,H_0}, P_{I,W,H_1}, P_{S,W,H_0}, and $P_{C,W}$) as the CCA-determined system idle probability under true H_0 or H_1 system state, successful transmission probability under H_0, and probability of collision, respectively. Here, P_{I,L,H_1} is the probability that mis-detection in the LAA nodes on the current LAA or WLAN

TABLE I: Definition of common symbols and expressions frequently used in this paper.

Symbol or Expression	Definition
S_L^{HC} (or S_L^{SC})	Throughput of LAA link with hard collision (or soft collision).
P_{I,L,H_0} (or P_{I,L,H_1})	Idle probability of LAA system under true H_0 (or H_1) case.
P_{S,L,H_0} (or P_{S,W,H_0})	Successful transmission probability of LAA (or WLAN), valid under H_0 only.
$P_{C,L}$ (or $P_{C,W}$)	Collision probability of LAA (or WLAN) system.
$P_{\text{Fa},L}$ and $P_{m,L}$ (or $P_{\text{Fa},W}$ and $P_{m,W}$)	False alarm and mis-detection probabilities of LAA (or WLAN)
τ_{L,H_0} (or τ_{L,H_1})	Channel access probability (CAP) of an LAA link under true H_0 (or H_1) case.
$\mathbf{P}_L^{\text{P-CCA}}$ (or $\mathbf{P}_L^{\text{E-CCA}}$)	Backoff state probability transition matrix with perfect CCA (or erroneous CCA).

transmission event has not caused improper transmissions, and so does not contribute to a collision immediately. Based on hard-collision retransmission model of LAA and WLAN, the sum of MAC throughput of n_L LAA nodes and n_W WLAN nodes are, respectively, given by

$$S_L^{\text{HC}} = P_{S,L} P_{I,W} T_{P,L} / T_{\text{ave},L}, \quad (2)$$
$$S_W^{\text{HC}} = P_{S,W} P_{I,L} T_{P,W} / T_{\text{ave},W}, \quad (3)$$

where $T_{\text{ave},L}$ and $T_{\text{ave},W}$ are the average total durations to support one successful transmission in LAA and WLAN systems, respectively. $P_{S,L}$ refers to the STP in the LAA system. This occurs when only one LAA node starts transmission in an idle slot (with probability P_{S,L,H_0}), and then the rest of $n_L - 1$ LAA links, even with possible mis-detection of this transmission, have not caused a collision (with probability $\hat{P}_{I,L,H_1}$). Here, we use P (or $\hat{P}$) to denote probabilities of this system observed by another system (or by its own system). $P_{I,W}$ in (2) is the probability that none of the n_W WLAN links is active during the observation of the LAA transmission. Thus, $P_{S,L}P_{I,W}$ in (2) gives the overall STP of the LAA links. In detail, we obtain:

$$P_{S,L} = P_{S,L,H_0} \hat{P}_{I,L,H_1} \quad (4)$$
$$P_{S,W} = P_{S,W,H_0} \hat{P}_{I,W,H_1}, \quad (5)$$
$$P_{I,L} = P_{I,L,H_0} P_{I,L,H_1}, \quad (6)$$
$$P_{I,W} = P_{I,W,H_0} P_{I,W,H_1}, \quad (7)$$

where $P_{S,L,H_0} = n_L \tau_{L,H_0} (1-\tau_{L,H_0})^{n_L - 1}$, and $P_{S,W,H_0} = n_W \tau_{W,H_0} (1-\tau_{W,H_0})^{n_W-1}$. Thus, we obtain for the LAA system that $P_{I,L,H_0} = (1-\tau_{L,H_0})^{n_L}$, $P_{I,L,H_1} = (1-\tau_{L,H_1})^{n_L}$, $\hat{P}_{I,L,H_0} = (1-\tau_{L,H_0})^{n_L-1}$, and $\hat{P}_{I,L,H_1} = (1-\tau_{L,H_1})^{n_L-1}$. Similarly, we have for the WLAN system that $P_{I,W,H_0} = (1-\tau_{W,H_0})^{n_W}$, $P_{I,W,H_1} = (1-\tau_{W,H_1})^{n_W}$, $\hat{P}_{I,W,H_0} = (1-\tau_{W,H_0})^{n_W-1}$, and $\hat{P}_{I,W,H_1} = (1-\tau_{W,H_1})^{n_W-1}$.

The collision probability among the LAA links is

$$\begin{aligned} P_{C,L} &= 1 - P_{I,L,H_0} - P_{S,L} \\ &= P_{C,L,H_0} + \hat{P}_{C,L,H_1}, \end{aligned} \quad (8)$$

where $P_{C,L,H_0} = 1 - P_{I,L,H_0} - P_{S,L,H_0}$ is the probability of collisions which are not related with mis-detection events, and $\hat{P}_{C,L,H_1} = P_{S,L,H_0}(1-\hat{P}_{I,L,H_1})$ refers to the probability that an initial transmission starts without collision, but then collision happens due to mis-detection(s).

To evaluate the throughput of LAA and WLAN systems under CCA errors, we still need to obtain τ_{L,H_0} and τ_{L,H_1}, and $T_{\text{ave},L}$ for LAA, and τ_{W,H_0}, τ_{W,H_1}, and $T_{\text{ave},W}$ for WLAN, respectively.

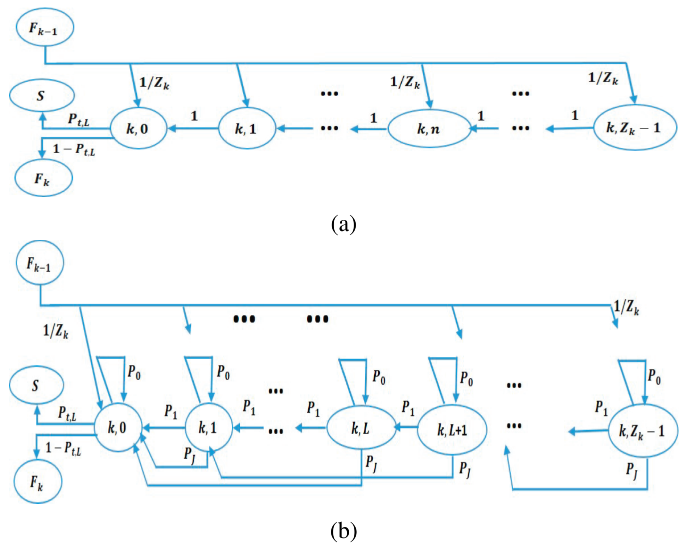

Fig. 1: Proposed Markov model of a CSMA/CA backoff process in one stage (a) without CCA errors (b) with CCA errors.

B. Modeling and Analysis of the Backoff Process

We develop a new probability analysis method involving probability transition matrix in the Markov chain to model the LAA and WLAN CW countdown process, when both systems have CCA errors. We show the backoff-and-transmission Markov transition model in Fig. 1(a) and (b), for the cases of perfect sensing and with CCA errors, respectively. F_{k-1} (and F_k) refers to state of failed transmission at backoff stage $k-1$ (and k), S refers to state of successful transmission, and $P_{t,L}$ is the conditional STP once a transmission starts. In Fig. 1(b), P_0 and P_1 are the probabilities that the counter value does not change, and reduces by one, respectively, during observation of one discrete event. Here, $P_0 > 0$ is caused by false alarm. The P_J in Fig. 1(b) refers to a CR up to J-step, caused by mis-detection of an ongoing transmission when the CCA errors are highly correlated. This means that an CCA error event can spread up to J CCA slot durations.

Consider a Category-3 LAA listen before talk (LBT) process [2], [3], which has a single backoff stage with CW range

$(0, Z_0-1)$. The result can be extended to a multi-stage backoff scheme. Let the backoff counter stationary probability vector be $\mathbf{b}_L = [b_0, b_1, \ldots, b_{Z_0-1}]^T$, where b_k is the probability that the backoff process stays at counter k. Define $\mathbf{P}_L$ as the $Z_0 \times Z_0$ Markov probability transition matrix for $\mathbf{b}_L$. When the backoff process of an LTE-LAA node achieves a steady state, via the limiting distribution property of stationary Markov chain [21], we obtain

$$\mathbf{b}_L = \mathbf{P}_L \mathbf{b}_L. \tag{9}$$

So, $\mathbf{b}_L$ can be solved as the null vector of matrix $\mathbf{I}_{Z_0} - \mathbf{P}_L$, subject to $\sum_{k=0}^{Z_0-1} b_k = 1$, where $\mathbf{I}_Z$ is an $Z \times Z$ identity matrix.

By mapping the backoff probability transition in matrix form, we derive the probability transition matrix with perfect CCA (P-CCA):

$$\mathbf{P}_L^{\text{P-CCA}} = \begin{bmatrix} 1/Z_0 & 1 & 0 & \ldots & 0 \\ 1/Z_0 & 0 & 1 & \ddots & \vdots \\ \vdots & \vdots & \ddots & \ddots & 0 \\ \vdots & \vdots & \vdots & 0 & 1 \\ 1/Z_0 & \vdots & \vdots & 0 & 0 \end{bmatrix}. \tag{10}$$

By solving (9) and (10), it follows that $b_0 = 2/(1+Z_0)$, which matches with the result in [7], [12], [16] for a given backoff stage. Also, all elements in $\mathbf{b}_L$ can be solved uniquely.

Stand-alone LAA System with CCA Errors

We list the probability and duration pairs at counter k in Table II, where we define events C_I = {Idle channel}, C_S= {Successful transmission}, C_C = {Immediate collision}, and C_{SC} = {No collision initially, but collision happens later due to mis-detection}, and denote their probabilities as P_{C_I}, P_{C_S}, P_{C_C}, and $P_{C_{SC}}$, respectively. We can verify that $P_{C_I} + P_{C_S} + P_{C_C} + P_{C_{SC}} = 1$, as expected.

Define $L_{S,L} = \text{round}(T_{S,L}/\delta)$ and $L_{C,L} = \text{round}(T_{C,L}/\delta)$, where $\text{round}(x)$ rounds x to its nearest integer. We denote the CR steps (or called lengths) caused by C_S and C_{SC} (normalized by δ) events in mis-detection as J_1 and J_2, respectively. We obtain $J_1 = L_{S,L}$ and $J_2 = L_{S,L} + L_{C,L}$, respectively, which are the normalized length of successful or failed transmission durations. When an LAA packet with length $L_{S,L}$ experiences a mis-detection in an LAA sensing node, this causes a CR of up to $\hat{J}_1 = \min(Z_0-1, L_{S,L})$ in the backoff process of this node. We denote this by the probability P_{J_1}. Also, $\hat{J}_2 = \min(Z_0 - 1, L_{S,L} + L_{C,L})$. Based on Table II, we obtain:

$$\begin{aligned} P_0 &= \hat{P}_{I,L,H_0} P_{\text{Fa},L}, & (11)\\ P_1 &= \hat{P}_{I,L,H_0}(1 - P_{\text{Fa},L}) + \hat{P}_{S,L,H_0}(1 - P_{m,L}) & \\ &\quad + P_{C,L,H_0}, & (12)\\ P_{J_1} &= \hat{P}_{S,L,H_0}\hat{P}_{I,L,H_1} P_{m,L} & (13)\\ P_{J_2} &= \hat{P}_{S,L,H_0}(1 - \hat{P}_{I,L,H_1}) P_{m,L}, & (14) \end{aligned}$$

where P_{J_k} (for $k = 1, 2$) is the probability that the counter value reduces by $\hat{J}_k$, due to mis-detection of an ongoing transmission. The effect of P_0, P_1 and P_{J_k} is shown in Fig. 1(b). For conciseness, we show only one jump transition path due to P_{J_k} $(k = 1, 2)$ in Fig. 1. (b).

Coexisting LAA and WLAN Systems with CCA Errors

Refer to Table III. For convenience, we assume that $T_{C,L} = T_{C,W} = T_C$. We use C_I and C_C to denote idle channel event and collision event that has a fixed duration T_C, respectively. We use $C_{S,L}$ (or $C_{S,W}$) to denote successful transmission of an LAA (or WLAN) link, and $C_{SC,L}$ (or $C_{SC,W}$) to denote initial LAA (or WLAN) link transmission which fails later due to collisions caused by mis-detection. Let $P_{C_1}, \ldots, P_{C_4}$ denote the probabilities of the 4 channel busy events for $C_{S,L}, C_{SC,L}, C_{S,W}, C_{SC,W}$, respectively. We obtain:

$$\begin{aligned} P_{C_1} &= \hat{P}_{S,L} P_{I,W}, & (15)\\ P_{C_2} &= \hat{P}_{S,L,H_0} P_{I,W,H_0} - \hat{P}_{S,L} P_{I,W}, & (16)\\ P_{C_3} &= \hat{P}_{I,L} P_{S,W}, & (17)\\ P_{C_4} &= \hat{P}_{I,L,H_0} P_{S,W,H_0} - \hat{P}_{I,L} P_{S,W}. & (18) \end{aligned}$$

We verify that $P_{C_I} + P_{C_C} + P_{C_1} + P_{C_2} + P_{C_3} + P_{C_4} = 1$, which shows that Table III provides a complete probability set.

We construct the counter state probability transition matrix with erroneous-CCA as

$$\mathbf{P}_L^{\text{E-CCA}} = \mathbf{P}_{L,0} + \sum_{k=1}^{4} \mathbf{P}_{L,J_k}, \tag{19}$$

where $\mathbf{P}_{L,0}$ is a transition matrix caused by regular backoff and false alarm events, and is given by

$$\mathbf{P}_{L,0} = \begin{bmatrix} 1/Z_0 & P_1 & 0 & \ldots & 0 \\ 1/Z_0 & P_0 & P_1 & \ddots & \vdots \\ \vdots & \vdots & \vdots & \ddots & 0 \\ \vdots & \vdots & \vdots & P_0 & P_1 \\ 1/Z_0 & \vdots & \vdots & 0 & P_0. \end{bmatrix} \tag{20}$$

where P_0 and P_1 refer to probabilities of no CR and 1-step CR, respectively. They are derived as

$$\begin{aligned} P_0 &= \hat{P}_{I,L,H_0} P_{I,W,H_0} P_{\text{Fa},L}, & (21)\\ P_1 &= \hat{P}_{I,L,H_0} P_{I,W,H_0}(1 - P_{\text{Fa},L}) & \\ &+ [\hat{P}_{S,L,H_0} P_{I,W,H_0} + \hat{P}_{I,L,H_0} P_{S,W,H_0}](1 - P_{m,L}) & \\ &+ \hat{P}_{C,L,H_0} P_{I,W,H_0} + \hat{P}_{I,L,H_0} P_{C,W,H_0} & \\ &+ (1 - \hat{P}_{I,L,H_0})(1 - P_{I,W,H_0}). & (22) \end{aligned}$$

When there are no CCA errors, we have $P_1 = 1$ and $P_0 = 0$, and (20) is simplified to (10), as expected. The impact of mis-detection is studied next.

Based on Table III, we derive the $T_{\text{ave},L}$ as

$$\begin{aligned} T_{\text{ave},L} &= P_{C_I}\delta_L + P_{C_C} T_C + P_{C_1} T_{S,L} + P_{C_2}(T_{S,L} + T_C) & \\ &\quad + P_{C_3} T_{S,W} + P_{C_4}(T_{S,W} + T_C) & (23) \end{aligned}$$

where the hat sign on $\hat{P}_{I,L,H_0}$, $\hat{P}_{C,L,H_0}$ and $\hat{P}_{S,L,H_0}$ involved in $P_{C_I}, P_{C_C}, P_{C_1}, P_{C_2}, P_{C_3}$, and P_{C_4} should be removed. The formula for $T_{\text{ave},W}$ can be obtained by following a similar procedure.

In (19), $\mathbf{P}_{L,J_k}$ is a matrix that models mis-detection related

TABLE II: Backoff probability and duration pairs at LAA node (Stand-alone LAA system).

Event	Event Probability	Sensing Probability & CR step (case 1)	Sensing Probability & CR step (case 2)
C_I	$\hat{P}_{I,L,H_0}$	$P_{\mathrm{Fa},L}$ and 0	$1-P_{\mathrm{Fa},L}$ and 1
C_C	$\hat{P}_{C,L,H_0}$	NA and 1	
C_S	$\hat{P}_{S,L}$	$P_{m,L}$ and $\hat{J}_1$	$1-P_{m,L}$ and 1
C_{SC}	$\hat{P}_{S,L,H_0}-\hat{P}_{S,L}$	$P_{m,L}$ and $\hat{J}_2$	$1-P_{m,L}$ and 1.

TABLE III: Backoff probability and duration pairs at LAA node (Coexisting LAA and WLAN systems).

Event	Event Probability	Sensing Probability and CR step (case 1)	Sensing Probability and CR step (case 2)
C_I	$P_{C_I}=\hat{P}_{I,L,H_0}P_{I,W,H_0}$	$P_{\mathrm{Fa},L}$ and 0	$1-P_{\mathrm{Fa},L}$ and 1
C_C	$P_{C_C}=\hat{P}_{C,L,H_0}P_{I,W,H_0}+\hat{P}_{I,L,H_0}P_{C,W,H_0}$ $+(1-\hat{P}_{I,L,H_0})(1-P_{I,W,H_0})$	NA and 1	
$C_{S,L}$	$P_{C_1}=\hat{P}_{S,L}P_{I,W}$	$P_{m,L}$ and $\hat{J}_1$	$1-P_{m,L}$ and 1
$C_{SC,L}$	$P_{C_2}=\hat{P}_{S,L,H_0}P_{I,W,H_0}(1-\hat{P}_{I,L,H_1}P_{I,W,H_1})$	$P_{m,L}$ and $\hat{J}_2$	$1-P_{m,L}$ and 1.
$C_{S,W}$	$P_{C_3}=\hat{P}_{I,L}P_{S,W}$	$P_{m,L}$ and $\hat{J}_3$	$1-P_{m,L}$ and 1
$C_{SC,W}$	$P_{C_4}=P_{S,W,H_0}\hat{P}_{I,L,H_0}(1-\hat{P}_{I,L,H_1}P_{I,W,H_1})$	$P_{m,L}$ and $\hat{J}_4$	$1-P_{m,L}$ and 1.

event P_{C_k} (for $k=1,\ldots,4$), and is given by

$$\mathbf{P}_{L,J_k}=\begin{bmatrix} 0 & \mathbf{P}_{J_k} & 0 & \cdots & 0 \\ 0 & 0 & \mathbf{P}_{J_k} & \ddots & 0 \\ \vdots & \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & 0 & \mathbf{P}_{J_k} \end{bmatrix} \tag{24}$$

where $\mathbf{P}_{J_k}=[P_{J_k}(1),\ldots,P_{J_k}(\hat{J}_k)]$, and $P_{J_k}(n)$ ($n=1,\ldots,\hat{J}_k$) is the transition probability for a n-step CR. Here, $\hat{J}_k$ (for $k=1,2,3,4$) are the CR sizes due to the 4 mis-detection events. We obtain $\hat{J}_1=\min(Z_0-1,L_{S,L})$, $\hat{J}_2=\min(Z_0-1,L_{S,L}+L_{C,L})$, $\hat{J}_3=\min(Z_0-1,L_{S,W})$ and $\hat{J}_4=\min(Z_0-1,L_{S,W}+L_{C,W})$, where $L_{S,W}=\mathrm{round}(T_{S,W}/\delta)$ and $L_{C,W}=\mathrm{round}(T_{C,W}/\delta)$.

The $\mathbf{P}_{L,0}$ completely models the effect of false alarm, and $\mathbf{P}_{L,J_k}$ (for $k=1,2,3,4$) additionally models the effect of mis-detection. Next, we derive $P_{J_k}(n)$ for correlated and independent CCA errors, respectively.

Correlated CCA Errors

In a slow fading channel, the mis-detection of the first slot of the packet is highly correlated with the detection of the remaining part of the packet. We assume the detection results in multiple slots to be fully correlated, and obtain:

$$P_{J_k}(n)=\begin{cases} 0, & \text{when } n\in(1,\ldots,\hat{J}_k-1) \\ P_{C_k}P_{m,L}, & \text{when } n=\hat{J}_k. \end{cases} \tag{25}$$

Here, $P_{J_k}(1)=\cdots=P_{J_k}(\hat{J}_k-1)=0$ because if the mis-detection occurs, it will spread until the last slot of the transmission. Furthermore, we can evaluate the case of partially-correlated CCA errors by developing a semi-analytical approach, which will be addressed in our future work.

Independent CCA Errors

In a fast fading channel, if the channel gain or power varies significantly between adjacent CCA slots, the CCA errors may be approximated as being uncorrelated among slots. We obtain an approximate solution to the transition probability of n-step CR of event J_k as

$$P_{J_k}(n)\simeq\binom{\hat{J}_k}{n}P_{C_k}P_{m,L}^{n}(1-P_{m,L})^{\hat{J}_k-n}. \tag{26}$$

Here, $\binom{\hat{J}_k}{n}$ denotes the binomial coefficient that mis-detection of n slots happens in a $\hat{J}_k$-slot duration. Based on knowledge of busy slot durations of transmissions, a better sensing decision strategy may be developed. For example, if a sensing node makes an H_1 decision, the node can use a larger time window than idle slot duration δ to do sensing for the rest of channel busy period, and achieve a more reliable detection performance.

C. Transmission Probabilities

Channel Access Probabilities (CAP)

By using the new state transition probability analysis, we derive the CAP τ_{L,H_0} as

$$\tau_{L,H_0}=b_{L,1}P_1+b_{L,0}/Z_0, \tag{27}$$

where $b_{L,1}P_1$ refers to transition from counter 1 to 0 without mis-detection, and $b_{L,0}/Z_0$ is the probability of counter reset after either a successful or failed transmission. Also, we have

$$\tau_{L,H_1}=\sum_{k=1}^{4}\sum_{n=1}^{\hat{J}_k}P_{J,k}(n)b_{L,n}, \tag{28}$$

where $P_{J,k}(n)b_{L,n}$ is the probability that the counter of this LAA link reduces from n to zero after mis-detection of event J_K. The CAPs τ_{W,H_0} and τ_{W,H_1} in the WLAN system can be obtained using a similar procedure, omitted here for brevity.

Successful Transmission Probabilities

In deriving (2) through (7), it is assumed that τ_{L,H_0} and τ_{L,H_1} are independent, so are τ_{W,H_0} and τ_{W,H_1}. A slightly more accurate result can be obtained if we drop this independence assumption. Then we obtain improved formulas to replace (4)–(7), shown below,

$$\begin{aligned} P_{S,L} &= n_L \tau_{L,H_0}(1-\tau_{L,H_0}-\tau_{L,H_1})^{n_L-1} && (29)\\ P_{S,W} &= n_W \tau_{W,H_0}(1-\tau_{W,H_0}-\tau_{W,H_1})^{n_W-1}, && (30)\\ P_{I,L} &= (1-\tau_{L,H_0}-\tau_{L,H_1})^{n_L}, && (31)\\ P_{I,W} &= (1-\tau_{W,H_0}-\tau_{W,H_1})^{n_W}. && (32) \end{aligned}$$

We derive the conditional STPs (conditioned upon that a transmission starts) of LAA and WLAN systems as

$$\begin{aligned} P_{t,L} &= (1-\tau_{L,H_0}-\tau_{L,H_1})^{n_L-1}(1-\tau_{W,H_0}-\tau_{W,H_1})^{n_W}\\ P_{t,W} &= (1-\tau_{L,H_0}-\tau_{L,H_1})^{n_L}(1-\tau_{W,H_0}-\tau_{W,H_1})^{n_W-1}. \end{aligned}$$

Based on (2), (3), (4)–(7), and (23), the throughput and other KPIs of LAA and WLAN links with CCA errors and hard-collisions can be evaluated.

D. *Throughput Under CCA Errors and Soft-Collision*

In the soft-collision case, we assume that H-ARQ is used for the miss-detection caused collided packets, and reduces the collision loss. With CCA-SC, the recovered payload for the LAA system is

$$\alpha_L(P_{S,L,H_0}P_{I,W,H_0}-P_{S,L}P_{I,W})T_{P,L} \qquad (33)$$

where α_L ($0 \le \alpha_L < 1$) is the packet recovery ratio due to soft combining of collided packets, and $(P_{S,L,H_0}P_{I,W,H_0} - P_{S,L}P_{I,W})$ refers to the probability that an original LAA transmission is corrupted by other LAA or WLAN links, but is later partially recovered.

We provide the soft-collision throughput for the LAA and WLAN systems as

$$\begin{aligned} S_L^{\mathrm{SC}} &= \frac{1}{T_{\mathrm{ave},L}} T_{P,L}[P_{S,L}P_{I,W}\\ &\quad +(P_{S,L,H_0}P_{I,W,H_0}-P_{S,L}P_{I,W})\alpha_L], && (34)\\ S_W^{\mathrm{SC}} &= \frac{1}{T_{\mathrm{ave},W}} T_{P,W}[P_{S,W}P_{I,L}\\ &\quad +(P_{S,W,H_0}P_{I,L,H_0}-P_{S,W}P_{I,L})\alpha_W]. && (35) \end{aligned}$$

where α_W ($0 \le \alpha_W < 1$) is the packet recovery ratio of the WLAN system. Based on (34), (35), (4)–(7), and (23), the KPIs of the coexisting LAA and WLAN links with CCA sensing errors and soft-collisions can be readily evaluated.

A discussion about result in [11] is in order. The work [11] provided solid progress on the effect of CCA errors on a single CSMA/CA system. Yet, besides the restrictive assumption of independent CCA errors, some analytical steps in [11] involved major approximations. For example, in (11) of [11] the throughput was set to be equal to the successful transmission probability, which lacked theoretical justification. The key throughput result in (13) of [11] included effects of mis-detection and false alarm probabilities, but it could not be shown to be consistent to the result of perfect CCA even when the mis-detection and false alarm probabilities are set to zero therein. Nevertheless, results in [11] may be regarded as useful approximations for certain range of parameters.

IV. Numerical and Simulation Results

In this section, we provide both analytical and simulation results to show the impact of sensing errors on the coexistence KPI performance of LTE-LAA and WLAN links.

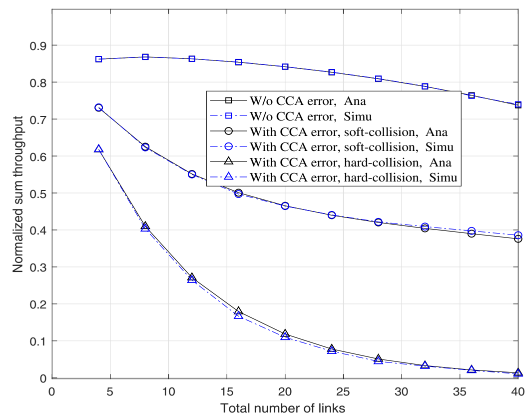

Fig. 2: Normalized sum throughput of the LTE-LAA and WLAN systems, when $P_{m,L} = P_{m,W} = 0.1$, $P_{\mathrm{Fa},L} = P_{\mathrm{Fa},W} = 0.1$, $W_0 = Z_0 = 32$, and $n_L + n_W$ changes from 4 to 40, with RTS/CTS scheme.

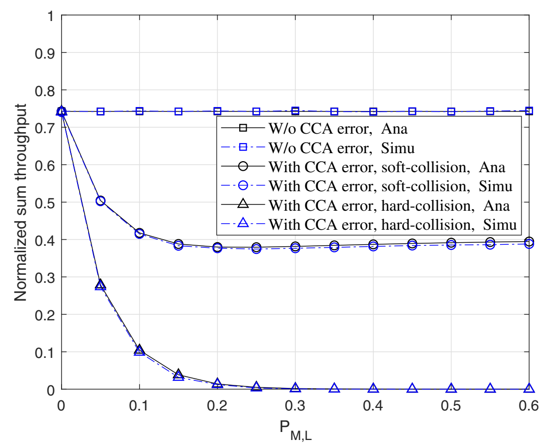

Fig. 3: Normalized sum throughput of the LTE-LAA and WLAN systems vs. $P_{m,L}$, when $n_L = n_W = 10$, $P_{\mathrm{Fa},L} = P_{\mathrm{Fa},W} = 0$, and $W_0 = Z_0 = 16$.

Both LTE-LAA and WLAN systems can use request-to-send/clear to send (RTS/CTS) type of handshaking schemes. Some CSMA/CA parameters and equations to compute $T_{S,L}$ (and $T_{C,L}$) from $T_{P,L}$, and to compute $T_{S,W}$ (and $T_{C,W}$) from $T_{P,W}$ are provided in [16], [17]. We set $\delta_L = \delta_W = \delta = 9$ μs following the default values [1], [6].

We assume a blockwise slow fading channel. This is realistic for the small cell or indoor fading channels which experience small Doppler spread. In computer simulation, we track all the backoff, transmission, and sensing error events, as described in Table III. Besides the case of perfect CCA, under CCA errors both hard-collision (CCA-HC) and soft collisions (CCA-SC) schemes are simulated (where we assume $\alpha_L = \alpha_W = 0.5$). On each parameter setting we ran the

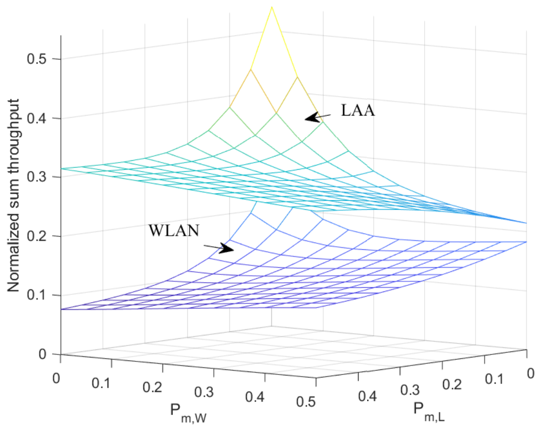

Fig. 4: Normalized sum throughput of the LTE-LAA and WLAN systems vs. $P_{m,L}$ and $P_{m,W}$ (from 0 to 0.5), respectively, when $n_L = n_W = 10$, $P_{\text{Fa},L} = P_{\text{Fa},W} = 0$, $W_0 = 32$, and $Z_0 = 16$.

algorithms for 10^5 time slots to obtain the average statistics on the throughput and transmission probabilities. We provide the time efficiency MAC throughput which is the time proportion of successful payload transmission of the system divided by the total observation duration. The normalized payload durations of LAA and WLAN are $L_{P,L} = L_{P,W} = 100$.

Fig. 2 shows the sum throughput of LAA and WLAN systems of 3 cases (without CCA errors, CCA-SC and CCA-HC) as $n_L + n_W$ increases. Fig. 3 provides the sum throughput vs. $P_{m,L}$, and the result shows that the throughput of the CCA-HC scheme decreases fast to zero when $P_{m,L} \simeq 0.2$, while the throughput of the CCA-SC scheme is partially maintained and robust against mis-detection. All results in Figs. 2 and 3 verify close matches among analytical and simulation results, and show that the proposed CCA-SC scheme is much more robust than the CCA-HC against CCA errors.

Finally, we provide analytical throughput of LAA and WLAN CCA-SC schemes vs. $P_{m,L}$ and $P_{m,W}$ in Fig. 4, which shows several observations: 1. The $P_{m,L}$ and $P_{m,W}$ affect the LAA and WLAN systems differently; 2. The LAA system has a higher throughput than the WLAN due to the CSMA parameter setting that $Z_0 = W_0/2$. This result suggests that we can use adaptive CSMA parameters (such as CW size and backoff stage) to achieve different throughput allocation even under CCA errors.

V. Conclusion

In this paper, we have modeled and evaluated the MAC layer performance of CSMA/CA coexisting systems (LTE-LAA and WLAN) assuming generalized CCA sensing errors. This technique applies to both slow fading (correlated CCA errors) and fast fading channels (independent CCA errors). To our knowledge, this is the first result that explicitly models generalized CCA errors on CSMA/CA backoff process, and provides accurate analysis of KPIs with applications to spectrum sharing systems. We have programmed LTE-LAA and WLAN MAC schemes under CCA errors and implemented extensive computer simulations, which have verified the accuracy of our analysis results. Simulation results have showed that sensing errors can significantly degrade the throughput, and the soft-collision method can reduce the performance loss substantially. These results have provided significant progress on the modeling, analysis, and mitigation of the impact of CCA errors on the CSMA/CA MAC layer, with application to coexistence systems. In the future work, we will implement hardware experiments, such as that reported in [18], to further validate our results.

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