Coexistence Analysis of LTE and WLAN Systems With Heterogenous Backoff Slot Durations

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Abstract— **To enable constructive coexistence with wireless local area networks (WLANs), unlicensed long-term evolution (LTE) systems use listen before talk (LBT) as a major candidate technique. The LBT has a flexible backoff idle slot duration, which can be significantly larger than the WLAN counterpart. To our knowledge, however, available analytical results on the LTE and WLAN coexistence have considered only identical idle backoff slot durations. There is a formidable technical difficulty to coexistence analysis for different backoff slot durations. In this paper, we develop a new technical approach to address this open issue. First, we point out an LBT backoff slot jamming effect, and propose a modified LBT backoff scheme to address this problem. Second, for our proposed LBT scheme, we develop a new analytical framework to address system interactions with non-equal backoff slot durations, model the LTE backoff process as super-counters, and provide a thorough analysis on the throughput, backoff counter hold time, and successful transmission probabilities of LTE-LBT and WLAN systems. Finally, we program the algorithms and use computer simulation to validate the analysis. This result fills a major gap and provides practical value for LTE-LBT and WLAN coexistence performance analysis with heterogeneous sensing and backoff slot durations.**

Index Terms: LTE; WLAN; Wireless System Coexistence; CSMA/CA; MAC-layer Performance Analysis.

I. Introduction

With the congestion and scarcity of available spectrum resources, spectrum sharing between long-term evolution license assisted access (LTE-LAA) and the IEEE 802.11 wireless local area network (WLAN) systems is a major ongoing research topic [1]–[6]. The 3rd Generation Partnership Project (3GPP) proposes to use listen before talk (LBT) to enable constructive coexistence between LAA and WLAN systems. The 3GPP LAA has defined 4 categories of LBT schemes [4], [5]. Category 3 and 4 LBT are system-load based sensing schemes, and have attracted significant interest. Various coexistence settings based on LTE-LAA and WLAN transmissions have been intensively evaluated, and experimental and field test results are reported in [4]–[6]. The WLAN uses carrier sense multiple access with collision avoidance (CSMA/CA) in the medium access control (MAC) layer, and load-based LBT uses a similar CSMA/CA method. However, due to the sensing reliability and other system requirement, the sensing (backoff slot) duration in the LBT Category 3 can be significantly larger than its counterpart in the WLAN [4].

Recently, some analytical approaches for the evaluation of LTE-LAA and WLAN coexistence systems have been developed, see e.g., [8]–[10]. Furthermore, optimization methods of the LAA and WLAN coexistence systems have been studied under various fairness constraints in [11]–[13].

However, to our knowledge, available analytical results are only valid when the backoff slot durations in different systems (such as the LAA and WLAN) are identical. The WLAN backoff (or idle/empty) slot duration includes clear channel assessment (CCA) time, and LAA backoff idle slot duration is equal to extended CCA (eCCA) time. In the current 3GPP development documents [4], [5], the LAA eCCA slot duration may be 20 μs or even larger, while the WLAN backoff slot duration (which includes CCA time) is 9 μs for several popular physical layer specifications [7]. Sensing performance of the LBT is closely related to eCCA sensing duration – a larger eCCA duration (aka. backoff duration) causes a better signal to noise ratio (SNR) for signal detection, but a slower backoff process, and vice versa. Robust and reliable detection of WLAN signals at LTE nodes, especially in multiparty fading channels, requires a reasonably large channel sensing duration (such as during eCCA). The channel sensing (and backoff slot) durations in different CSMA/CA-based systems are typically not identical, such as IEEE 802.15.4, IEEE 802.11, and LTE-LAA systems. Hence, analyzing the case of heterogeneous backoff slot durations will have important theoretical and practical value, useful for future coexistence applications of heterogeneous systems.

Available methods face formidable challenges to address the case of non-equal idle backoff slot durations. The Bianchi-proposed Markov chain method is a popular approach for CSMA/CA MAC-layer performance analysis [14], [15], and has been extended in [8]–[10] for coexistence analysis. However, this method is not flexible enough to model very complex coexisting behaviors in both the backoff phase and transmission phase, experienced in non-identical slot durations between coexistence systems. Recently, another method on WLAN MAC-layer performance analysis is provided in [16]–[18]. This method is more flexible than Bianchi's framework in that it explicitly models the backoff counter hold time, and uses a different set of statistics to compute the MAC-layer throughput. However, this method is based on assumption of identical backoff idle slot durations among all transmitting nodes.

Coexistence analysis between IEEE 802.15.4 and IEEE 802.11 WLAN systems has recently been implemented in [19], where the 802.15.4 devices are assumed to have a backoff slot duration three times as large as the counterpart WLAN nodes. However, besides the differences in the MAC protocols between LTE-LAA and the 802.15.4, the 802.15.4 device does not have the backoff slot frozen effect as the LAA node. Thus, the problem at hand is more difficult to solve.

In this paper, we model and solve this challenging problem. The contributions are highlighted as follows:

- We show that with heterogeneous backoff durations between LAA and WLAN systems, there is a previously-unknown backoff slot jamming effect to LAA nodes. We then propose a MAC scheme to avoid this negative effect.
- We develop a novel analysis tool to model the non-identical backoff slots, such as LTE super counters and weighted probability transition paths, to model interaction between LTE and WLAN nodes. Then we provide analytical results on the counter hold time, successful transmission probability, and throughput.
- We program the algorithms and implement extensive simulation to validate our analytical results on the co-existence performance.

This new technique fills a major gap in coexistence analysis of LTE-LAA and WLAN systems, and can be extended to the analysis of other CSMA/CA based heterogeneous wireless systems. The technical insight and method provided by this work may be used for optimization of coexisting systems.

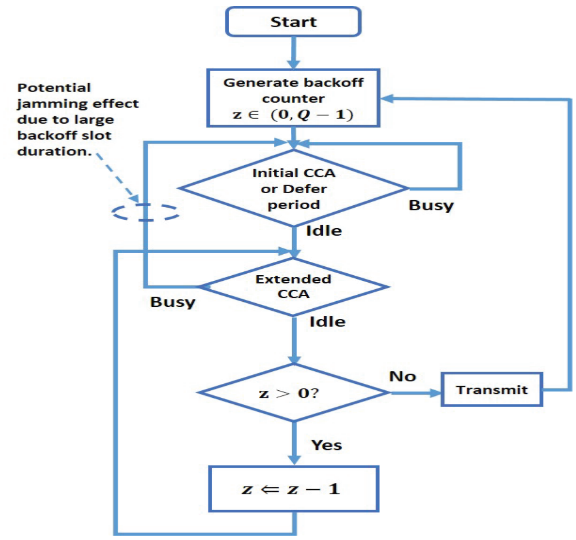

Fig. 1: Flow diagram of LTE downlink LAA LBT Category-3 procedure, adopted from [4], [5] with major revision. We mark the backoff slot jamming effect assuming that the LAA has backoff slot duration substantially larger than that of the WLAN system.

II. System Model

Here, we consider the case that LTE LAA utilizes only unlicensed spectrum for the downlink and shares it with incumbent WLAN users. The processing flow of LAA Category 3 LBT scheme is shown in Fig. 1, adopted from [4], [5]. In comparison with [4], [5], we switched the order of the blocks "$z > 0$" and "extended CCA". This revision lets the transmitter which finishes one transmission to wait for an eCCA period, in addition to initial CCA (or extended defer period), before a backoff counter reduction. This change is significant in that it makes sure that after a channel busy period, the active transmitter which finishes its transmission opportunity (TXOP) does not have more priority in next channel access than the competing stations.

Define $N_s = \delta_L/\delta_W$, where δ_L and δ_W are the backoff idle slot durations for LAA and WLAN, respectively. To facilitate smooth coexistence, we assume $T_{\text{DIFS}} = T_{\text{Defer}}$, where T_{DIFS} and T_{Defer} are WLAN distributed coordination function interframe spacing (DIFS) and LAA eCCA defer durations, respectively. In the LAA backoff counter reduction scheme, shown in Fig. 1 (and those in [4], [5]), by default, an LAA counter reduction is permitted in either of the two cases: 1) when the channel becomes idle for $T_{\text{DIFS}} + \delta_L$ right after channel busy state; 2) the channel becomes idle for δ_L right after previous counter reduction.

We point out that when $N_s > 1$, this LBT scheme can cause a slot jamming effect disadvantageous to the LAA station, not investigated in the available literature.

This slot-jamming effect is illustrated in Fig. 2 for the row "LAA states (default)" in the eCCA duration, assuming $N_s = 2$. In detail, an LAA counter reduction takes a longer duration ($N_s\delta_W$) than a WLAN counter reduction (δ_W), and before it reaches a slot boundary, a WLAN counter may first reduce to zero and begin transmission. After the channel busy state is over, the LAA node has to reset the counter value to the state before the WLAN transmission: that is, the reduction can be jammed if there are frequent WLAN transmissions (when $N_s > 1$); please refer to WLAN slots 4-6 in Fig. 2. Though the jamming does not happen in these slots, it can happen if any WLAN node reduces its counter to 0 from slot 5 to 6. Based on this observation, the jamming effect is due to that a WLAN node always has higher counter reduction opportunity in both cases 1 and 2 discussed above.

To address this problem, we propose a modified LAA Counter Reduction Scheme, shown next.

Proposed LAA Counter Reduction Scheme

1) Draw counter value $Z \in (0, Z_0 - 1)$, where Z_0 is the LAA initial contention window (CW) size. Wait until the channel is idle for initial CCA (iCCA) duration. If $Z = 0$, the LAA node transmits; otherwise, it goes to backoff stage.
2) Decrease counter Z by 1 in either of the following two channel idle cases:
   Case 1: Right after a channel busy state, if channel becomes idle for $T_{\text{DIFS}} + \delta_W$ (use $\delta_L = \delta_W$);
   Case 2: After the previous counter reduction, channel is idle again for $\delta_L = N_s\delta_W$.
3) If Z is reduced to zero, starts transmission. Restart from Step 1).

In our proposed LBT MAC scheme, in Case 1, LAA and WLAN nodes have equal priority in reducing their counter values. After an LAA counter reduction, if the idle period continues, then we still set $\delta_L = N_s\delta_W$, which enables an adequate slot period for channel sensing. The state transition and counter reduction for the proposed scheme is given by the row "LAA states (our proposed)" in Fig. 2. During WLAN

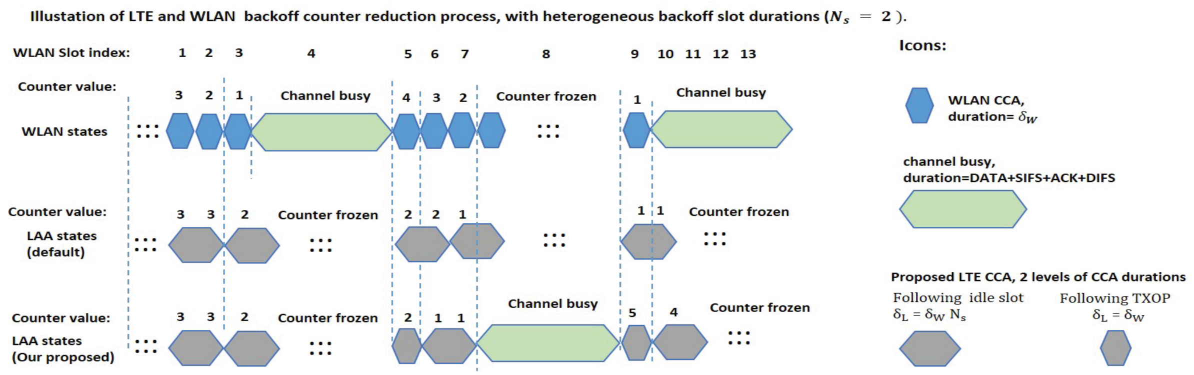

Fig. 2: Flow diagram of LTE and WLAN backoff counter reduction and transmission process, when the LAA has backoff slot duration twice as large as that of the WLAN system.

slot 5 to 6, the LAA idle slot is reduced from $N_s\delta_W$ to δ_W, providing equal counter reduction opportunity for all LAA and WLAN nodes after a channel busy state is over. In WLAN slot indexes 5 and 9 of Fig. 2, after the WLAN and LAA transmissions (channel busy), their counter values (4 and 5 respectively) were randomly generated based on their initial CW sizes. Furthermore, ACK and SIFS refer to acknowledgement signal duration and short interframe spacing, respectively.

Our scheme has two advantages: 1) It mostly avoids the slot jamming effect; 2) It causes only negligible impact on channel sensing accuracy of channel idle state in case 1, because although the total idle duration used for channel detection is reduced to $T_{\text{DIFS}} + \delta_W$ from $T_{\text{DIFS}} + N_s\delta_W$ (case 1), it is typically larger than $N_s\delta_W$ (case 2).

III. Performance Analysis

We developed a new Markov chain method to model the LAA CW countdown process, and its interactions with WLAN transmissions. The model is shown in Fig. 3. The basic backoff-and-transmission state transition model is shown in Fig. 3(a), and its equivalent expanded model for $N_s > 1$ is described in Fig. 3.(b). Based on the LTE-LAA Markov model in Fig. 3, a performance analysis of LTE and WLAN coexistence is provided next. In this section, we use subscripts L, W, i, S, C, p to denote LAA, WLAN, idle, successful transmission, collision, and payload, respectively. The MAC throughput of an LAA node and a WLAN node are, respectively, given by

$$S_L = \pi_{S,L}T_{p,L}/T_{\text{ave},L} \quad (1)$$

$$S_W = \pi_{S,W}T_{p,W}/T_{\text{ave},W}, \quad (2)$$

where $T_{p,L}$ and $T_{p,W}$ are payload durations, $\pi_{S,L}$ and $\pi_{S,W}$ are the probabilities of successful transmissions, and $T_{\text{ave},L}$ and $T_{\text{ave},W}$ are the average total durations caused by one successful transmission, in LAA and WLAN systems, respectively. Define $\pi_{F,L}$ and $\pi_{R,L}$ as probabilities for failed transmission and backoff stage, respectively. Based on the model in Fig. 3.(a), we have $\pi_{S,L} = 0.5P_{t,L}$, $\pi_{F,L} = 0.5(1 - P_{t,L})$, and $\pi_{R,L} = 0.5$, where $P_{t,L}$ is probability of successful transmission conditioned on that an LAA transmission starts.

Suppose that a WLAN node has cutoff stage M, with maximum CW size W_m at stage m, for $m = 0, 1, \ldots, M$. For a WLAN node, define $\pi_{F,W,m}$ and $\pi_{R,W,m}$ as probabilities for failed transmission and backoff, at stage m, respectively. Below, we use a method similar to that in [16], with one major difference that once the transmission at cut-off stage fails, the counter is reset to the initial stage ($m = 0$) immediately. By using the equality

$$\pi_{S,W} + \sum_{m=0}^{M}[\pi_{R,W,m} + \pi_{F,W,m}] = 1, \quad (3)$$

we can solve for the state probabilities as: $\pi_{S,W} = P_{t,W}/2$,

$$\pi_{R,W,0} = \frac{0.5P_{t,W}}{1 - (1 - P_{t,W})^{M+1}} \quad (4)$$

$$\pi_{R,W,m} = \pi_{R,W,0}(1 - P_{t,W})^m \quad (5)$$

$$\pi_{F,W,m} = \pi_{R,W,0}(1 - P_{t,W})^{m+1} \quad (6)$$

for $m = 0, \ldots, M$, where $P_{t,W}$ is the successful transmission probability given that a WLAN node transmission starts. Also,

$$T_{\text{ave},L} = \pi_{S,L}T_{S,L} + \pi_{F,L}T_{C,L} + 0.5T_{R,L}$$

$$T_{\text{ave},W} = \pi_{S,W}T_{S,W} + \sum_{m=0}^{M}[\pi_{F,W,m}T_{C,W} + \pi_{R,W,m}T_{R,W,m}],$$

where the $T_{S,L}$ ($T_{S,W}$) and $T_{C,L}$ (and $T_{C,W}$) are the channel busy durations due to successful transmission and collision, for LAA (and WLAN), respectively. The $T_{R,L}$ is the LTE counter hold time per transmission, and $T_{R,W,m}$ (and $P_{R,W,m}$) is the WLAN counter hold time (and probability) in backoff stage m, $m = 0, \ldots, M$.

Conditioned on a counter reduction, the transmission probability for LAA Category-3 node is derived as

$$\tau_L = 2/(1 + Z_0), \quad (7)$$

where Z_0 is the initial CW size of the LAA node. Define $\tilde{\pi}_{R_m} = \pi_{R,W,m}T_{R,W,m}/T_{\text{ave},W}$ as the normalized duration in backoff stage m. The transmission probability for a WLAN node is obtained as

$$\tau_W = 1 - \frac{\sum_{m=0}^{M} \tilde{\pi}_{R_m}(1 - 2/(1 + W_m))}{\sum_{m=0}^{M} \tilde{\pi}_{R_m}}. \tag{8}$$

It easily follows that

$$\begin{aligned} T_{R,L} &= \frac{Z_0 - 1}{2} T_{L,0} \\ T_{R,W,m} &= \frac{W_m - 1}{2} T_{W,0}, \end{aligned}$$

where $T_{L,0}$ and $T_{W,0}$ are the hold-time per counter reduction at LAA and WLAN nodes, respectively.

To compute MAC-layer throughput, we still need to find $T_{L,0}$, $P_{t,L}$ for the LAA, and $T_{W,0}$ and $P_{t,W}$ for the WLAN. Refer to Figs. 3 and 4: Even for the case of equal LTE and WLAN slot duration ($N_s = 1$), this model is different from those of available approaches [8]–[10], [14], [16]–[18]. For the case of $N_s > 1$, the difference is more significant.

To illustrate our method, we show the case of $N_s = 1$ first, and then we develop more details for the case of $N_s > 1$.

A. Equal Slot Duration ($N_s = 1$)

When $N_s = 1$, it follows that

$$\begin{aligned} P_{t,L} &= (1 - \tau_W)^{n_W}(1 - \tau_L)^{n_L - 1} \\ P_{t,W} &= (1 - \tau_W)^{n_W - 1}(1 - \tau_L)^{n_L}, \end{aligned}$$

where τ_W and τ_L are the transmitting (channel access) probabilities of WLAN and LAA systems, given by (8) and (7), respectively. Let P and $\hat{P}$ denote probabilities observed by a node when observing its own system (e.g., state of LAA system observed by an LAA node), and the other system (e.g., state of LAA system observed by a WLAN node), respectively. For example $P_{i,L} = (1 - \tau_L)^{n_L - 1}$, $P_{i,W} = (1 - \tau_W)^{n_W - 1}$, but $\hat{P}_{i,L} = (1 - \tau_L)^{n_L}$, and $\hat{P}_{i,W} = (1 - \tau_W)^{n_W}$.

Refer to Fig. 4: The feedforward path of $1 - \hat{P}_{i,W} P_{i,L}$ consists of 5 sub-events: LAA successful transmission (with probability $P_{S,L}$), LAA intra-system signal collision ($P_{C,L}$), WLAN successful transmission ($\hat{P}_{S,W}$), WLAN intra-system signal collision ($\hat{P}_{C,W}$), and LAA-WLAN inter-system signal collision (with probability $(1 - \hat{P}_{i,W})(1 - P_{i,L})$). When $N_s = 1$, we obtain an average counter hold time (per counter reduction) for an LAA node as

$$\begin{aligned} T_{L,0} &= P_{i,L}\hat{P}_{i,W}\delta_W + (P_{S,L}T_{S,L} + P_{C,L}T_{C,L})\hat{P}_{i,W} \\ &+ (\hat{P}_{S,W}T_{S,W} + \hat{P}_{C,W}T_{C,W})P_{i,L} \\ &+ (1 - \hat{P}_{i,W})(1 - P_{i,L})T_{C,M}, \end{aligned} \tag{9}$$

where $T_{C,M} = \max(T_{C,W}, T_{C,L})$, $\hat{P}_{S,W} = n_W \tau_W (1 - \tau_W)^{n_W - 1}$, $\hat{P}_{C,W} = 1 - \hat{P}_{i,W} - \hat{P}_{S,W}$,

$$P_{S,L} = \begin{cases} (n_L - 1)\tau_L(1 - \tau_L)^{n_L - 2}, & \text{when } n_L \geq 2; \\ 0, & \text{when } n_L \leq 1, \end{cases}$$

and $P_{C,L} = 1 - P_{i,L} - P_{S,L}$.

Similarly, we have the average counter hold time (per counter reduction) for a WLAN node as

$$\begin{aligned} T_{W,0} &= \hat{P}_{i,L}P_{i,W}\delta_W + (\hat{P}_{S,L}T_{S,L} + \hat{P}_{C,L}T_{C,L})P_{i,W} \\ &+ (P_{S,W}T_{S,W} + P_{C,W}T_{C,W})\hat{P}_{i,L} \\ &+ (1 - P_{i,W})(1 - \hat{P}_{i,L})T_{C,M}, \end{aligned} \tag{10}$$

where $\hat{P}_{S,L} = n_L \tau_L (1 - \tau_L)^{n_L - 1}$, $\hat{P}_{C,L} = 1 - \hat{P}_{i,L} - \hat{P}_{S,L}$,

$$P_{S,W} = \begin{cases} (n_W - 1)\tau_W(1 - \tau_W)^{n_W - 2}, & \text{when } n_W \geq 2; \\ 0, & \text{when } n_W \leq 1, \end{cases}$$

and $P_{C,W} = 1 - P_{i,W} - P_{S,W}$.

Based on the above results, the throughput of the LAA and WLAN nodes in the coexistence case with $N_s = 1$ can be readily evaluated.

B. Non-Equal Slot Durations ($N_s > 1$)

We need to consider two cases for the LAA backoff counter reduction:

1) channel is idle for $T_{\text{DIFS}} + \delta_W$ following a transmission (channel busy); and
2) channel is idle for $\delta_L = N_s \delta_W$ right after a previous counter reduction.

We model the transition paths between the two cases during an LAA counter reduction in Fig. 5. Define the probabilities of cases 1 and 2 as $\Pr(C_1)$ and $\Pr(C_2)$, and the transition probability from case n_1 to case n_2 as $\Pr(C_{n_2}|C_{n_1})$, for $n_1, n_2 \in (1, 2)$. For example, $\Pr(C_1|C_1)$ is the sum of all the probability paths from Case 1 (on the right side in Fig. 5) to Case 1 (on the left side), and $\Pr(C_1|C_1) = 1 - \hat{P}_{i,W} P_{i,L}$.

From Fig. 5, it follows that

$$\begin{aligned} \Pr(C_1) &= \Pr(C_1)(1 - P_{i,L}\hat{P}_{i,W}) + [\Pr(C_1) + \Pr(C_2)] \\ &\quad \cdot P_{i,L}\hat{P}_{i,W}[1 - P_{i,L}\hat{P}_{i,W}^{N_s}] \qquad (11) \\ \Pr(C_2) &= [\Pr(C_1) + \Pr(C_2)]P_{i,L}\hat{P}_{i,W}\hat{P}_{i,W}^{N_s - 1}. \qquad (12) \end{aligned}$$

We can verify that equations (11) and (12) are equivalent, as expected. To determine $\Pr(C_1)$ and $\Pr(C_2)$, we need one more equality. The sum probability of all the counter states within one counter reduction in Fig. 5 equals unity. Thus,

$$\begin{aligned} &\Pr(C_1) + [\Pr(C_1) + \Pr(C_2)]P_{i,L}\hat{P}_{i,W} \\ &\quad \cdot (1 + \hat{P}_{i,W} + \ldots + \hat{P}_{i,W}^{N_s - 1}) = 1. \end{aligned} \tag{13}$$

Based on (12) and (13), we derive:

$$\begin{aligned} \Pr(C_2) &= \left(\frac{1 - P_{i,L}\hat{P}_{i,W}^{N_s}}{P_{i,L}\hat{P}_{i,W}^{N_s}} + \frac{1 - \hat{P}_{i,W}^{N_s}}{\hat{P}_{i,W}^{N_s - 1} - \hat{P}_{i,W}^{N_s}} \right)^{-1} \\ \Pr(C_1) &= \Pr(C_2)\frac{1 - P_{i,L}\hat{P}_{i,W}^{N_s}}{P_{i,L}\hat{P}_{i,W}^{N_s}}. \end{aligned}$$

When $N_s = 1$, (11) and (12) reduce to

$$\begin{aligned} \Pr(C_1|N_s = 1) &= (1 - P_{i,L}\hat{P}_{i,W}) \qquad (14) \\ \Pr(C_2|N_s = 1) &= P_{i,L}\hat{P}_{i,W}, \qquad (15) \end{aligned}$$

as expected. This means that when $N_s = 1$, Case 1 corresponds to a channel busy event, which is always followed by DIFS and idle slot δ_W, and Case 2 corresponds to a channel idle event, where all LAA and WLAN nodes stay idle.

Successful transmission probabilities

Define $\Pr(\text{WTx})$ as the probability that only the WLAN node has transmit opportunity, and $\Pr(\text{JTx})$ as the probability that all LTE and WLAN nodes have transmit opportunity, respectively, from WLAN's observation. To compute $P_{t,W}$, refer to Fig. 5 again. $\Pr(\text{WTx})$ is the sum probability the

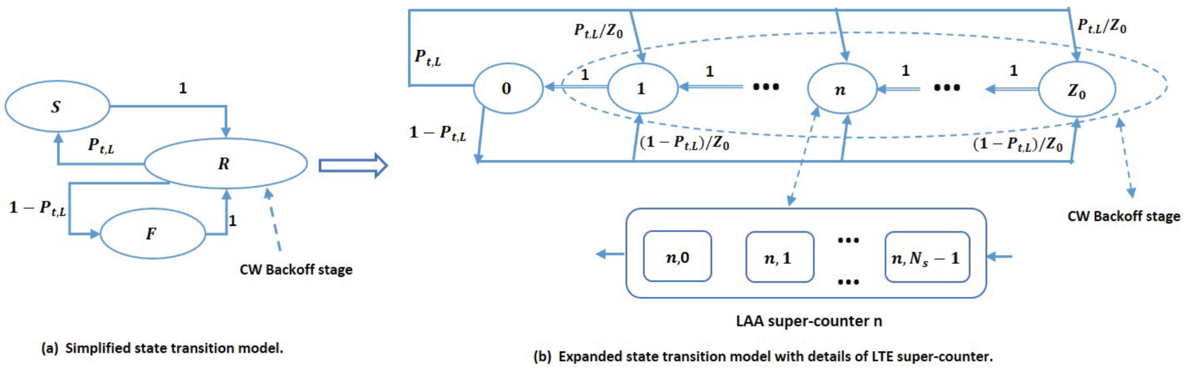

Fig. 3: Our proposed Markov model for the LTE-LAA LBT category 3 procedure in coexistence with WLAN.

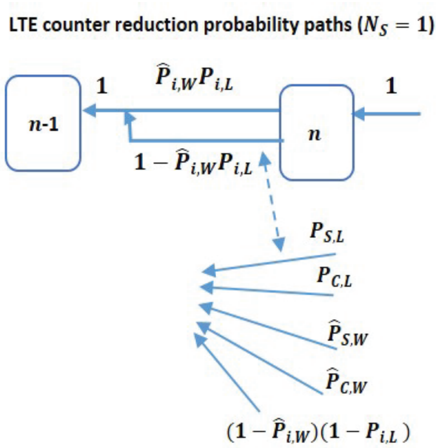

Fig. 4: Illustration of Markov model for the LAA counter reduction when $N_s = 1$.

$N_s - 1$ subcells in the right side of the super-counter. When $N_s \geq 2$, we have $\Pr(\text{JTx}) = 1 - \Pr(\text{WTx})$, and

$$\begin{aligned}\Pr(\text{WTx}) &= [\Pr(\tilde{C}_1) + \Pr(\tilde{C}_2)]\hat{P}_{i,L}P_{i,W} \\ &\quad \cdot(1 + P_{i,W} + \ldots + P_{i,W}^{N_s-2}) \qquad (16)\end{aligned}$$

where $\Pr(\tilde{C}_1)$ and $\Pr(\tilde{C}_2)$ are obtained from $\Pr(C_1)$ and $\Pr(C_2)$ by replacing $P_{i,L}$ and $\hat{P}_{i,W}$ with $\hat{P}_{i,L}$ and $P_{i,W}$ therein, respectively. With probability $\Pr(\text{WTx})$, all LAA nodes stay silent. Thus, the successful transmission probability of a WLAN node ($P_{t,W}$) is given by

$$\begin{aligned}P_{t,W} &= \Pr(\text{WTx})(1-\tau_W)^{n_W-1} \\ &+ \Pr(\text{JTx})(1-\tau_W)^{n_W-1}(1-\tau_L)^{n_L}. \qquad (17)\end{aligned}$$

We define successful transmission probability of an LAA node based on each counter reduction (which happens in Cases 1 and 2), then

$$P_{t,L} = (1-\tau_L)^{n_L-1}(1-\tau_W)^{n_W}, \qquad (18)$$

which is independent of N_s. This is because each LAA node can transmit only upon the two channel idle cases.

Average counter hold time for LAA and WLAN nodes

TABLE I: Probability and duration pairs to compute LAA counter hold time.

Probability ($P_{n,L}$)	Duration ($T_{n,L}$)
$\Pr(C_1)(1-P_{i,L}\hat{P}_{i,W})$	$\overline{T}_{L,W}$
$\Pr(C_1,C_2)(1-\hat{P}_{i,W})$	$\overline{T}_W$
$\Pr(C_1,C_2)(1-\hat{P}_{i,W})\hat{P}_{i,W}$	$\overline{T}_W + \delta_W$
$\ldots$	$\ldots$
$\Pr(C_1,C_2)(1-\hat{P}_{i,W})\hat{P}_{i,W}^{N_s-2}$	$\overline{T}_W + (N_s-2)\delta_W$
$\Pr(C_1,C_2)(1-\hat{P}_{i,W}P_{i,L})\hat{P}_{i,W}^{N_s-1}$	$\overline{T}_{L,W} + (N_s-1)\delta_W$
$\Pr(C_1,C_2)P_{i,L}\hat{P}_{i,W}^{N_s}$	$N_s\delta_W$

Refer to Fig. 5 again. The average hold time for an LAA node $T_{L,0}$ is obtained by summing the duration of each path from the start states to the end states, weighted by the path probability. The probability and duration pairs of each path is listed in Table I. In Table I, $\overline{T}_W$ is the average channel busy duration when any one or more WLAN nodes transmit, and $\overline{T}_{L,W}$ is the average channel busy duration when any one or more of the LAA and WLAN nodes transmit. They are given by

$$\begin{aligned}\overline{T}_W &= \frac{1}{(1-\hat{P}_{i,W})}[\hat{P}_{S,W}T_{S,W} + \hat{P}_{C,W}T_{C,W}] \\ \overline{T}_{L,W} &= \frac{1}{(1-\hat{P}_{i,W}P_{i,L})}[(\hat{P}_{S,W}T_{S,W} + \hat{P}_{C,W}T_{C,W})P_{i,L} \\ &+ (P_{S,L}T_{S,L} + P_{C,L}T_{C,L})\hat{P}_{i,W} \\ &+ (1-\hat{P}_{i,W})(1-P_{i,L})T_{C,M}].\end{aligned}$$

In Table I, the first item is for the direct path through the regular counter on the top side, from Case 1 to Case 1 which is a channel busy event. The 2nd to (N_s+1)th terms are for the paths through the super-counter on the bottom side from both Cases 1 and 2 to Case 1, which are channel busy events. The final term ((N_s+2)th term) is for the 0th subcell in the super-counter, from Case 2 to Case 2. In Table I,

$$\Pr(C_1, C_2) = [\Pr(C_1) + \Pr(C_2)]\hat{P}_{i,W}P_{i,L}, \qquad (19)$$

which corresponds to the path from Cases 1 and 2 in slot $n+1$ to the super-counter in slot n. Finally, $T_{L,0}$ can be computed

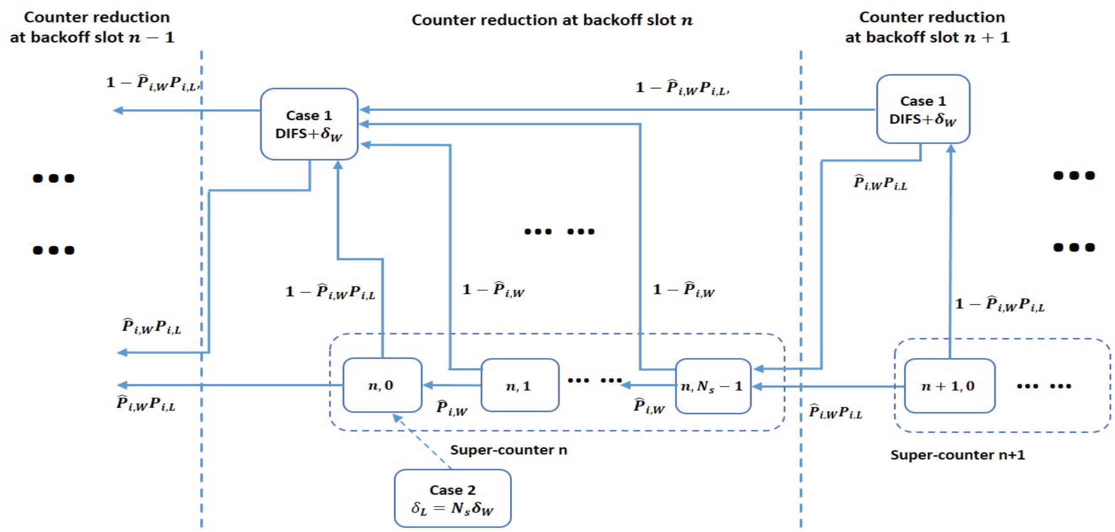

Fig. 5: Flow diagram for LAA counter backoff probability paths.

by summing up all the probability-weighted durations in Table I, that is

$$T_{L,0} = \frac{1}{\Pr(C_1)+\Pr(C_2)}\sum_{n=1}^{N_s+2} P_{n,L}T_{n,L}, \tag{20}$$

where the normalization by factor $\Pr(C_1)+\Pr(C_2)$ is used, because an LAA node transmits only upon the two idle cases with sum probability $\Pr(C_1)+\Pr(C_2)$.

When $\overline{T}_W \gg \delta_W$ and $\overline{T}_{L,W} \gg \delta_W$, we obtain an approximate formula for $T_{L,0}$:

$$\begin{aligned} T_{L,0} \simeq\ & \frac{\Pr(C_1)(1-P_{i,L}\hat{P}_{i,W})}{\Pr(C_1)+\Pr(C_2)}\overline{T}_{L,W} + \hat{P}_{i,W}P_{i,L} \\ & \times\ [(1-\hat{P}_{i,W}^{N_s-1})\overline{T}_W + \hat{P}_{i,W}^{N_s-1}(1-P_{i,L}\hat{P}_{i,W})\overline{T}_{L,W}]. \end{aligned}$$

By use of the concept of joint transmission and WLAN-only transmission, average hold time $T_{W,0}$ for a WLAN node is derived as

$$T_{W,0} \simeq \Pr(\text{WTx})\tilde{T}_W + \Pr(\text{JTx})\tilde{T}_{W,L}, \tag{21}$$

where

$$\begin{aligned} \tilde{T}_W &= P_{S,W}T_{S,W} + P_{C,W}T_{C,W} + P_{i,W}\delta_W \\ \tilde{T}_{W,L} &= P_{i,W}\hat{P}_{i,L}\delta_W + (P_{S,W}T_{S,W} + P_{C,W}T_{C,W})\hat{P}_{i,L} \\ &+ (\hat{P}_{S,L}T_{S,L} + \hat{P}_{C,L}T_{C,L})P_{i,W} \\ &+ (1-P_{i,W})(1-\hat{P}_{i,L})T_{C,M}. \end{aligned}$$

Based on results above, the coexistence performance of LAA and WLAN with non-equal idle slot durations can be readily evaluated.

IV. Numerical Results

In this section, we provide both analytical and simulation results of the coexistence behavior of LTE-LAA links with WLAN links. The proposed LBT backoff counter reduction scheme is used. The simulation results were obtained by running for 10^5 time slots on each parameter setting. The parameters used for analysis and simulation are listed in Table II, where the WLAN parameters were adopted from [6], [9], [15], with basic access scheme. We assume that the WLAN and LAA systems have channels fully overlapped at the 5 GHz industrial, scientific, and medical (ISM) band. When the transmission time efficiency is 100%, the upper bound for the physical layer channel bit rate (CBR) is set to 100 Mega bits per second (Mbps) for both the LAA and WLAN systems.

TABLE II: LTE and WLAN Parameters in Simulation.

LTE parameters

Parameter	Value
Payload duration per transmission	2 ms
$T_{L,\text{SIFS}}$	16 μs
LBT defer period: T_{Defer} (=T_{DIFS})	34 μs
LBT eCCA period: T_{eCCA} (=$N_s\delta_W$)	$N_s \times 9$ μs
Initial CW size Z_0	8

WLAN parameters

Parameter	Value
Payload duration per transmission	1 ms
MAC and PHY headers	272 and 128 bits
T_{SIFS}	16 μs
T_{DIFS}	34 μs
Idle slot duration δ_W	9 μs
Initial CW size W_0	16

We show the average counter hold durations for the LAA and WLAN systems in Fig. 6, and the throughput results in Fig. 7, respectively, assuming $N_s = 3$, and $n_L + n_W$ changes from 4 to 28. We observe that the analytical and simulation results match very well. From Fig. 6, as total number of links $n_W + n_L$ increases, the gap between counter hold durations among LAA and WLAN nodes decreases, and this corresponds

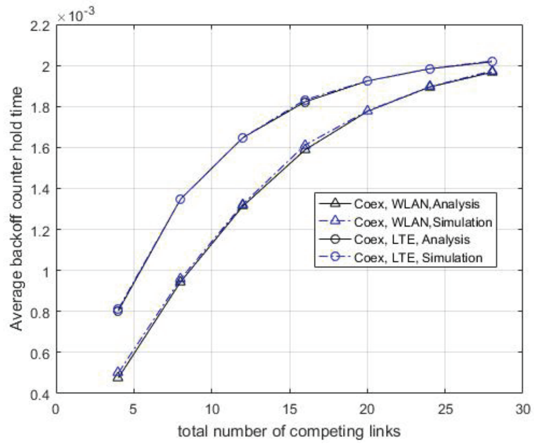

Fig. 6: Counter hold times of LTE and WLAN systems, when $N_s = 3$, $M = 3$, and $n_L + n_W$ changes from 4 to 28.

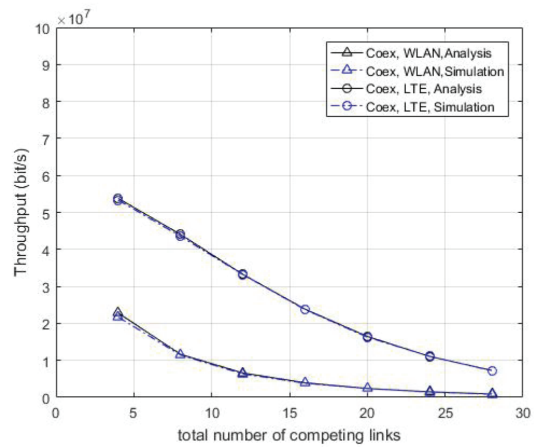

Fig. 7: Throughput of LTE and WLAN systems, when $N_s = 3$, $M = 3$, and $n_L + n_W$ changes from 4 to 28.

to a better access fairness for LAA nodes based on our proposed LBT scheme. For results not shown here, when the original LBT is used, this gap is significantly larger and LAA nodes experience a backoff jamming effect. The related analysis and simulation result is not shown here due to space limitation. From Fig. 7, we observe that throughput of LAA and WLAN systems decrease with number of links. The LAA system has larger throughput because it uses half the CW size ($Z_0 = W_0/2$), although its idle slot duration is 3 times that of the WLAN system.

V. Conclusion

In this paper, we have studied the impact of heterogeneous backoff slot durations on the MAC-layer performance of LTE-LAA coexisting with WLAN transmissions. We first pointed out a slot-jamming effect due to difference in backoff idle slot durations, and proposed an LBT slot backoff scheme to avoid this problem. To evaluate the coexistence performance, we have developed a novel Markov chain approach with several new features to capture the complicated coexistence behaviors caused by different backoff slot durations. Then, we provided analytical results on the backoff counter hold time, successful transmission probability and throughput. We have implemented LTE and WLAN MAC scheme programming and extensive computer simulation, which have verified our analysis results. The new analytical tool can be leveraged for CSMA parameter optimization in coexisting systems, and provide theoretical support for related measurement and experiment. In future work, our method can be extended to coexistence of other CSMA/CA based wireless systems, and the effects of various fading channel models will be studied.

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