MAC-Layer Coexistence Analysis of LTE and WLAN Systems Via Listen-Before-Talk

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Abstract— **With the congestion and scarcity of available spectrum resources, spectrum sharing between long-term evolution (LTE) and the IEEE 802.11 (aka. WLAN) systems is an ongoing research topic. Considering the LTE license assisted access (LAA) with the listen before talk (LBT) procedure, recent research efforts try to evaluate the performance in several LTE-LBT and WLAN coexistence scenarios. However, the available approaches have not adequately modeled and analyzed general case of LBT (such as Category 4), and the case when there are more than two types of transmissions. In this paper, to fill this technical gap, we implement a systematic modelling and analysis of the media access control (MAC) layer coexisting performance of LTE-LBT and WLAN systems. We consider the coexistence scenario of multiple LTE downlink with multiple WLAN uplink and downlink transmissions. We develop analytical results on time-efficiency throughput, transmission and collision probabilities of LTE and WLAN nodes, and then generalize the result to multiple types of transmissions (e.g., more than three types). To validate the analysis, we implement LBT and WLAN MAC algorithm programming and extensive simulations, which confirm the accuracy of our analysis. Our result shows that replacing WLAN stations with LTE transmitters may, in some cases, significantly degrade the overall throughput, depending on the original efficiencies of WLAN systems and channel access schemes. To address this, we propose a 4-way handshaking channel access scheme for LTE-LBT, which can significantly improve the coexistence performance. These results put new insight into relationship between coexistence performance and MAC parameters of LTE-LBT and WLAN systems, and may aid in the design and optimization of coexistence systems.**

I. Introduction

To enable the coexistence between cellular and IEEE 802.11 wireless local area network (WLAN) systems in the industrial, scientific, and medical (ISM) radio band, the long-term evolution (LTE) with license assisted access (LAA) has been proposed and studied by the 3rd Generation Partnership Project (3GPP), industry, and research community [1]–[7]. Constructive coexistence between unlicensed LTE with WLAN relies on proper medium access control (MAC) layer channel access coordination between the heterogeneous systems. To avoid destructive collision between LTE and other radio systems, the 3GPP LAA has proposed features such as dynamic carrier selection, discontinuous transmission with limited maximum transmission duration, transmit power control, and listen before talk (LBT) [4], [5], [7].

The LAA has defined 4 categories of LBT schemes [5], [6]. Category 1 has no LBT, and category 2 defines LBT without random back-off, related to the frame-based (FBE) sensing and access. Category 3 LBT includes random back-off with fixed size of contention window (CW), and category 4 LBT uses variable size of CW with multiple-stage random back-off [5]. Among them, Categories 3 and 4 LTE-LBT schemes implement load-based coexistence, and have attracted major interest from the telecom industry and research community. Various coexistence settings based on LTE-LBT and WLAN transmissions have been intensively evaluated, and abundant experimental and field test results are reported in [5]–[7].

Recently, some analytical approaches for the performance evaluation of LTE-LBT and WLAN coexistence systems have been developed, see e.g. [8], [9]. In [8], coexistence of WLAN access points (APs) and LTE-LBT downlink transmissions is modelled and analyzed. The LTE-LBT transmission uses higher data rate when there is no collision, and a low rate when a collision is detected. In another LTE-LBT scheme [9], LTE base stations (BSs) share unlicensed spectrum with WLAN APs in downlink transmissions, and the overall system throughput is examined when some APs are replaced by an equal number of BSs. The work in [8], [9] evaluate only Category-3 LBT schemes, and analytical curves are provided as numerical result (there is no evidence that simulation results are provided in [8], [9]).

Some recent work [10]–[12] try to optimize the coexistence performance under various fairness constraints. In [10], the authors propose an LBT scheme that has short initial clear channel assessment (CCA) duration, which controls the access priority of LTE and WLAN systems. They develop optimization method to maximize the LTE-LAA system performance under constraint of fair channel sharing with the WLAN system. A new LBT protocol was developed in [11] to maximize the LTE and WLAN overall normalized channel rate by adjusting the LTE transmission durations, under a constraint of protection to WLAN service. In [12], an adaptive LBT scheme was developed to satisfy the quality of service (QoS) requirement of LTE users under condition that the resulting collision probability of WLAN users is constrained.

While the above mentioned [8]–[12] and other works provide new performance evaluation and optimization methods on LTE-LAA and WLAN coexistence, the general case of Category-4 LTE-LBT based coexistence has not been clearly modelled and well analyzed. Furthermore, in most of the available works, only two types of transmissions were considered, namely WLAN downlink and LTE LBT-based downlink.

However, future coexistence applications will likely involve three or more types of transmissions, and related performance analysis is lacking.

In this paper, we study the coexistence of multiple types of LTE-LBT and WLAN transmissions with different parameters, and provide a stationary steady-state analysis method of channel access probability, collision probability, and throughput, assuming saturated transmissions. Many recent works claim that the overall throughput performance is typically enhanced by replacing some WLAN APs with LTE nodes [5], [7], [9]. Here, we try to examine the conditions when the overall performance improves or degrades, supported by simulation.

The contribution of this paper is highlighted as follows:

- Following Category-4 LBT given by recent 3GPP LTE-LAA document [5], we provide new performance analysis that is valid for multiple types of LTE and WLAN transmissions, and generalize the analysis to more than 3 types of transmissions.
- We implement computer programming and extensive simulation to evaluate the MAC-layer coexistence of LTE-LBT and WLAN systems, and validate our analytical results.
- Our results show that the coexistence sum throughput may either improve or degrade when WLAN APs are replaced by LTE nodes, depending on system parameters and efficiency of the original WLAN system. Also, we propose a 4-way handshaking access scheme for LTE LBT, which is shown to provide significantly enhanced coexistence performance.

Finally, our new analytical result can be utilized for optimization design of general LBT schemes in coexistence scenario.

The remainder of this paper is organized as follows: Section II describes the LTE and WLAN coexistence system model, and Section III presents the performance analysis for Category-4 LBT assuming 3 types of transmissions. Technical discussions are provided in Section IV, and numerical results and conclusions are given in Sections V and VI, respectively.

II. System Model

Suppose several LTE small cells with N_L enhanced NodeB's (eNBs) coexist with multiple WLAN networks. The LTE-LAA utilizes carrier aggregation (CA), with primary traffic on licensed channels and secondary traffic on unlicensed channels. It shares the unlicensed channels with WLAN transmissions, and hence the LBT is important for system coexistence. Note that the LTE and WLAN aggregation (LWA) is another spectrum sharing candidate technique, which relies on dual connectivity of licensed LTE and unlicensed WLAN systems, and allows the LTE traffic to be carried by WLAN transmissions. The study of the LWA method is outside the scope of this paper.

Here, we consider the case that LTE LAA utilizes only unlicensed spectrum and shares it with incumbent WLAN users. In this model, the LTE-LBT downlink transmissions coexist with incumbent WLAN downlink and uplink transmissions in the same spectrum band, and all of them have

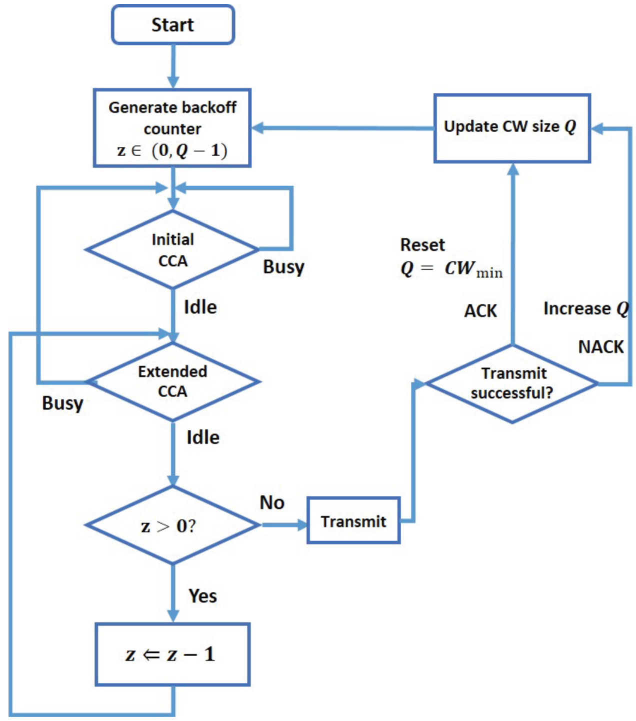

Fig. 1: Flow diagram of LTE downlink LAA LBT Category-4 procedure (adopted from [5], [6] with modifications).

saturated incoming traffic. In WLAN enhanced distributed channel access (EDCA), based on QoS requirement, different transmissions may belong to different access categories in terms of arbitration inter-frame space (AIFS), transmission duration, and initial CW size and backoff cut-off stage [18], [19]. In the model considered here, we assume that WLAN uplink and downlink transmissions have different CW sizes. We propose an LTE downlink LAA Category-4 LBT scheme adopted from [5] and [6], and show it in Fig. 1. It is modified from Fig. 7.2.1.6.1 of [5] in that we remove the buffer idle states, and explicitly show the relation between CW size Q and the receiver acknowledgement. It is also related to the Category-3 LBT figure given in [6] which has fixed CW size. In comparison with [5] and [6], we made one additional major change that the order of blocks "extended CCA" and "$z > 0$" is switched in Fig. 1. This change removes the channel access priority of an LAA node which just finishes a transmission, and makes it different from the case of transmission of a WLAN node.

The initial CCA in Fig. 1 has dual purposes: it implements initial channel sensing of duration T_{iCCA} to avoid collision with other transmissions, and it is implemented after a busy channel (either successful transmission or collision), for a duration called defer period T_{Defer} [5], [6]. When the counter z is reduced to 0, transmission starts. The CW size is adjusted based on ACK and NACK responses via hybrid automatic repeat request (HARQ) from the receiver. We assume that after NACK, the CW size is doubled until the cutoff stage is reached, similarly to the WLAN distributed coordination function (DCF) procedure.

III. Performance Analysis

A. Markov Model of Category-4 LBT Procedure

Based on Fig. 1, we provide a Markov chain-based modelling of the LTE-LBT process in Fig. 2, which has maximum backoff stage R_L (also called cutoff stage). In each stage, the counter decrements when the channel is sensed idle for an extended CCA duration, denoted as T_{eCCA}. When the backoff counter is reduced to 0, an LTE downlink transmission starts. The $P_{f,L}$ is the probability that the LTE eNB experiences collision when it senses the channel idle and transmits. When we consider only the 0th backoff stage (with fixed CW size), this Markov chain state diagram models a Category-3 LBT process.

It appears that the Markov model in Fig. 2 is similar to the model given in [13], [15]. They are related and yet have some differences. First, after active transmission, the LTE node has to wait for channel idle duration $T_{\text{iCCA}}+T_{\text{eCCA}}$, before counter decrement. We assume that $T_{\text{Defer}} = T_{\text{iCCA}} = T_{\text{DIFS}}$, where T_{DIFS} is the WLAN DCF inter-frame space (DIFS) duration. Define δ_L as an LBT idle slot (or eCCA) duration. In Fig. 1, we let the LTE node with a successful transmission to wait for an additional δ_L, so that it does not have priority over other competing stations. This is in contrast to the WLAN transmission case [15]. The difference is reflected in the stage 0 backoff counter in Fig. 2, where in [15] the backoff CW size after successful transmission is shorter than the CW size after a collision. Second, MAC parameters of LTE LBT procedure may be different from those of WLAN. The transmission packet duration of LTE is assumed to be larger than the WLAN packet duration in this paper. To facilitate the coexistence analysis, however, we assume that $\delta_L = \delta_W$, where δ_W is the backoff idle slot duration of WLAN system.

B. Stationary Probability and Throughput Analysis

Based on the LTE-LBT Markov model in Fig. 2, a performance analysis of LTE and WLAN coexistence is provided next. The conditional state transition probabilities are given by:

$$P(0,k|j,0) = (1-P_{f,L})/Z_0, \quad j \in [0, R_L-1] \quad (1)$$

$$P(0,k|R_L,0) = P_{f,L}/Z_0, \quad (2)$$

$$P(j,k|j,k+1) = 1, \quad j \in [0,R_L], k \in [0, Z_j-2] \quad (3)$$

where Z_j is the CW size at backoff stage j, $j = 0, 1, \ldots, R_L$, $k \in (0, Z_j-1)$ is the backoff counter value, and R_L is the cutoff stage for LTE Category-4 LBT.

We define $\pi_{j,k}$ as the stationary probability of state (j,k). Using π as stationary probability of Markov state is consistent with the notations used in the literature [17], [18]. From eqs. (1)–(3) it follows that:

$$\pi_{j,0} = p_{f,L}^{j}\pi_{0,0}, \quad j \in [0, R_L],$$

$$\pi_{j,k} = \frac{Z_j - k}{Z_j}\pi_{j,0} \quad k \in [0, Z_j-1]; j \in [0, R_L].$$

Using the fact that total probability of all states is 1, we have $\sum_{j=0}^{R_L}\sum_{k=0}^{Z_j-1}\pi_{j,k} = 1$, and obtain that

$$\pi_{0,0} = \left[0.5\sum_{j=0}^{R_L} p_{f,L}^{j}(1+Z_j)\right]^{-1}.$$

The transmission probability of each LTE station is given by:

$$\tau_L = \sum_{j=0}^{R_L}\pi_{j,0} = \pi_{0,0}\frac{1-p_{f,L}^{R_L+1}}{1-p_{f,L}} = \frac{2(1-p_{f,L}^{R_L+1})}{(1-p_{f,L})\sum_{j=0}^{R_L}p_{f,L}^{j}(1+Z_j)}. \quad (4)$$

The joint stationary probability distribution of LTE and WLAN networks based on Markov process is provided next. We assume that LTE and WLAN systems have the same slot duration δ in the counter idle slots, which is the same as that considered in [8], [9]. We define the failed transmission probabilities (due to packet collisions) of LTE, and WLAN downlink and uplink systems as $p_{f,L}$, p_{f,W_D}, and p_{f,W_U}; corresponding transmission (or channel access) probabilities as τ_L, τ_{W_D}, and τ_{W_U}; the initial CW sizes as Z_0, $W_{0,D}$, and $W_{0,U}$; and the cutoff stages as R_L, R_D and R_U, respectively.

Based on [15], the transmission probabilities of a WLAN node in downlink and uplink transmissions are given by:

$$\tau_{W_D} = \frac{1}{1+\frac{1-p_{f,W_D}}{2(1-p_{f,W_D}^{R_D+1})}\left[\sum_{j=0}^{R_D}p_{f,W_D}^{j}(2^jW_{0,D}-1)-(1-p_{f,W_D}^{R_D+1})\right]}, \quad (5)$$

$$\tau_{W_U} = \frac{1}{1+\frac{1-p_{f,W_U}}{2(1-p_{f,W_U}^{R_U+1})}\left[\sum_{j=0}^{R_U}p_{f,W_U}^{j}(2^jW_{0,U}-1)-(1-p_{f,W_D}^{R_U+1})\right]}. \quad (6)$$

The probabilities of failed transmissions in LTE and WLAN systems are derived as:

$$p_{f,W_D} = 1-(1-\tau_{W_D})^{n_{W_D}-1}(1-\tau_{W_U})^{n_{W_U}}(1-\tau_L)^{n_L}, \quad (7)$$

$$p_{f,W_U} = 1-(1-\tau_{W_U})^{n_{W_U}-1}(1-\tau_{W_D})^{n_{W_D}}(1-\tau_L)^{n_L}, \quad (8)$$

$$p_{f,L} = 1-(1-\tau_L)^{n_L-1}(1-\tau_{W_D})^{n_{W_D}}(1-\tau_{W_U})^{n_{W_U}}, \quad (9)$$

where $\tau_L, \tau_{W_D}, \tau_{W_U}$ are given by (4), (5), and (6), respectively. Eqs. (4)-(9) model 6 unknowns in 6 equalities, and they can be solved by using an iterative numerical search method. Numerical evaluation shows that the iteration was stable and accurate for the considered range of parameters. The iterative search method for solving the transmission and collision probabilities has been used popularly in the literature, for example in [8], [9], [13]–[15].

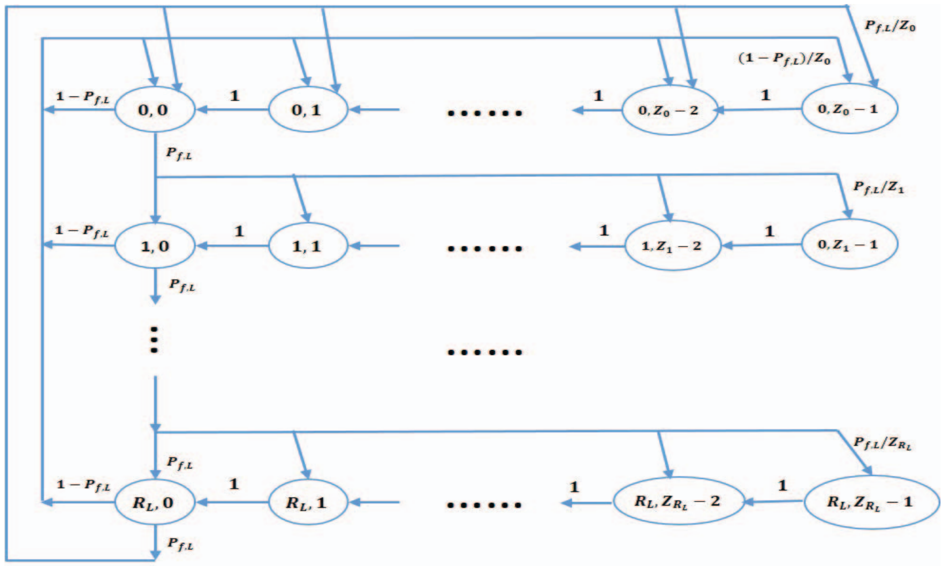

Fig. 2: Markov model of LTE-LAA LBT category 4 procedure.

Let P_{s,W_D}, P_{s,W_U}, and $P_{s,L}$ be the successful transmission probabilities, T_{P,W_D}, T_{P,W_U}, $T_{P,L}$ be the corresponding payload durations, and P_{b,W_D}, P_{b,W_U}, and $P_{b,L}$ be the probabilities of busy states (node transmitting), for WLAN downlink, uplink and LTE systems, respectively.

The MAC-layer sum throughput (normalized successful transmission time-duration) for WLAN downlink, uplink and LTE transmissions are given by:

$$S_{W_D} = P_{s,W_D}(1-P_{b,W_U})(1-P_{b,L})\overline{T}_{P,W_D}/T_{\text{ave}}, \quad (10)$$
$$S_{W_U} = P_{s,W_U}(1-P_{b,W_D})(1-P_{b,L})\overline{T}_{P,W_U}/T_{\text{ave}}, \quad (11)$$
$$S_L = P_{s,L}(1-P_{b,W_D})(1-P_{b,W_U})T_{P,L}/T_{\text{ave}}, \quad (12)$$

where $\overline{T}_{P,W_D} = T_{P,W_D}W_{0,D}/(W_{0,D}-1)$, $\overline{T}_{P,W_U} = T_{P,W_U}W_{0,U}/(W_{0,U}-1)$, respectively. Furthermore, we have

$$P_{s,W_D} = n_{W_D}\tau_{W_D}(1-\tau_{W_D})^{n_{W_D}-1}, \quad (13)$$
$$P_{s,W_U} = n_{W_U}\tau_{W_U}(1-\tau_{W_U})^{n_{W_U}-1}, \quad (14)$$
$$P_{s,L} = n_L\tau_L(1-\tau_L)^{n_L-1}, \quad (15)$$
$$P_{b,W_D} = 1-(1-\tau_{W_D})^{n_{W_D}}, \quad (16)$$
$$P_{b,W_U} = 1-(1-\tau_{W_U})^{n_{W_U}}, \quad (17)$$
$$P_{b,L} = 1-(1-\tau_L)^{n_L}. \quad (18)$$

In (10)–(12), T_{ave} is the average time duration spent when a packet is sent successfully from either WLAN or LTE system. The T_{ave} is given by

$$\begin{aligned} T_{\text{ave}} &= (1-P_{b,W_D})(1-P_{b,W_U})(1-P_{b,L})\delta \\ &+ P_{s,W_D}(1-P_{b,W_U})(1-P_{b,L})\overline{T}_{s,W_D} \\ &+ P_{s,W_U}(1-P_{b,W_D})(1-P_{b,L})\overline{T}_{s,W_U} \\ &+ P_{s,L}(1-P_{b,W_D})(1-P_{b,W_U})T_{s,L} \\ &+ P_{c,WW}(1-P_{b,L})T_{c,W} \\ &+ P_{c,LL}(1-P_{b,W})T_{c,L} + P_{c,WL}T_{c,M}, \end{aligned} \quad (19)$$

where $\overline{T}_{s,W_D} = \delta + T_{s,W_D}\frac{W_{0,D}}{W_{0,D}-1}$ and $\overline{T}_{s,W_U} = \delta + T_{s,W_U}\frac{W_{0,U}}{W_{0,U}-1}$ are the effective transmission durations of WLAN downlink and uplink, respectively, following a method in [15]. In (19), T_{s,W_D}, T_{s,W_U} and $T_{s,L}$ (or T_{c,W_D}, T_{c,W_U} and $T_{c,L}$) are durations of channel busy condition caused by one successful transmission (or collision), respectively. The $\delta = \delta_L = \delta_{W_D} = \delta_{W_U}$, where $\delta_L, \delta_{W_D}, \delta_{W_U}$ are idle slot durations of the three types of transmissions. Furthermore, $T_{c,W} = \max(T_{c,W_D}, T_{c,W_U})$, and $T_{c,M} = \max(T_{c,W}, T_{c,L})$.

The $P_{c,WW}$, $P_{c,LL}$, $P_{c,WL}$ refer to WLAN intra-system collision probability, LTE intra-system collision probability, and WLAN LTE inter-system collision probability, respectively:

$$P_{c,WW} = P_{b,W} - P_{s,W}, \quad (20)$$
$$P_{c,LL} = P_{b,L} - P_{s,L}, \quad (21)$$
$$P_{c,WL} = P_{b,W}P_{b,L}, \quad (22)$$

where

$$P_{b,W} = 1-(1-\tau_{W_D})^{n_{W_D}}(1-\tau_{W_U})^{n_{W_U}}, \quad (23)$$
$$\begin{aligned} P_{s,W} &= P_{s,W_D}(1-P_{b,W_U}) + P_{s,W_U}(1-P_{b,W_D}) \\ &= n_{W_D}\tau_{W_D}(1-\tau_{W_D})^{n_{W_D}-1}(1-\tau_{W_U})^{n_{W_U}} \\ &+ n_{W_U}\tau_{W_U}(1-\tau_{W_U})^{n_{W_U}-1}(1-\tau_{W_D})^{n_{W_D}}. \end{aligned} \quad (24)$$

The first term on the right hand side (RHS) of (19) gives the average idle duration, the 2nd to 4th terms on the RHS provide the average successful transmission durations of the three types of transmissions, and the 5th to 7th terms provide the average collision durations, respectively. Our approach shown in (19) is concise and flexible in computing the throughput statistics. It decouples the idle, successful transmission, and collision events of each type of transmission, and then groups the events (or related probabilities) properly to compute the statistics.

By substituting (13)–(24) into (10)–(12), the average throughput (time efficiency) of WLAN and LTE systems can be evaluated. This method is more concise and flexible than those developed in [8], [9], and easily scalable to the case of multiple coexisting types of transmissions (even more than three).

IV. Technical Extension and Discussions

A. Generalization to Coexistence of Multiple Systems

In future coexistence applications, the number of types of transmissions may be larger than three. It is of practical interest to develop a general coexistence performance analysis method valid for multiple types of transmissions, as shown next. Assume N types of transmissions, and each transmission involves n_i nodes (or links), for $i = 1, \ldots, N$. Define δ, $T_{s,i}$, $T_{c,i}$, respectively, as the durations of counter idle slot, successful transmission, and collision; and $P_{f,i}$, $P_{b,i}$, $P_{s,i}$, respectively, as the probabilities of a failed transmission, channel busy (at the counter decrement phase), and successful transmission, for a node in transmission type i.

The steps of analytical evaluation are described below. First, construct the Markov chain based on the MAC layer scheme, and find the channel access probability of transmission type i ($i = 1, \ldots, N$), given by

$$\tau_i = g_i(P_{f,i}, Z_i, R_i) \tag{25}$$

where Z_i, R_i are the initial CW size and cutoff stage of type i, respectively, and g_i is the mapping function based on the MAC scheme of type i. For example, τ_i in (25) is provided by eqs. (4), (5), (6), for LTE-LBT and WLAN downlink and uplink systems, respectively. Next,

$$P_{f,i} = 1 - (1 - \tau_i)^{n_i - 1} \prod_{\substack{j \neq i \\ j=1}}^{N} (1 - \tau_j)^{n_j}. \tag{26}$$

For N types of transmissions, eqs. (25) and (26) involves $2N$ equations and $2N$ unknowns $\{f_i, \tau_i\}_{i=1,\ldots,N}$, which can be solved uniquely by iterative numerical research techniques.

The sum throughput of transmission type i is derived as

$$\begin{aligned} S_i &= P_{s,i} \prod_{\substack{j \neq i \\ j=1}}^{N} (1 - P_{b,j}) T_{s,i}/T_{\text{ave}} \\ &= n_i \tau_i (1 - \tau_i)^{n_i - 1} \prod_{\substack{j \neq i \\ j=1}}^{N} (1 - \tau_j)^{n_j} T_{s,i}/T_{\text{ave}} \end{aligned} \tag{27}$$

where T_{ave} is the average duration spent for each transmission type to send one payload successfully. Its formula is given by (28), shown on the top of the next page.

The first, second and third terms in (28) refer to durations for events of channel idle, successful transmission, and collision within one transmission type, respectively. The fourth and last terms refer to durations of collisions of two different types of transmissions, and simultaneous collisions of all types of transmissions, respectively. The skipped terms in (28) are durations of collisions among three types to $(N-1)$ types, whose notations are obvious and omitted here for the brevity of presentation.

B. LTE LBT Hand-Shaking Schemes

To evaluate the LTE transmission and collision durations $T_{s,L}$ and $T_{c,L}$ needed in (19), we propose two candidate hand-shaking schemes. The first one is similar to the WLAN basic access scheme, where the LTE transmission phase includes a 2-way handshaking: downlink data transmission and uplink ACK/NACK response. In the first setting (LBT basic channel access),

$$T_{s,L} = T_{P,L} + T_{\text{Defer}}, \tag{29}$$

$$T_{c,L} = T_{s,L}, \tag{30}$$

where the T_{Defer} (= T_{DIFS}) is the required defer period. Based on the method in Fig. 1, LTE transmitter's priority over the non-transmitting stations is removed. Notice that in DCF we have

$$T_{s,W} = T_{P,W} + T_{\text{SIFS}} + T_{\text{ACK}} + T_{\text{DIFS}}, \tag{31}$$

where T_{SIFS} and T_{ACK} are the short inter-frame space (SIFS) and ACK packet durations, respectively. In comparison, $T_{s,L}$ does not have terms T_{SIFS} and T_{ACK}. We explain it as follows: It is stated in [5] that the downlink HARQ-ACK timing rules from Release-12 carrier aggregation (CA) can be reused at least for DL-only LAA transmissions. This means that the delay between LTE transmission and the ACK/NACK response is on the order of several milliseconds (ms), much larger than the WLAN DCF SIFS (which in DCF is the delay between transmission and ACK/NACK). The milliseconds level of ACK/NACK delay involved in LTE-LAA does not block the other nodes for accessing the channel, and thus it is not counted in $T_{s,L}$. In the first scheme, when the LTE collision happens, the data packets sent in transmission duration are lost and the cost of collision may be high.

To improve the MAC efficiency, as the second setting, we propose an RTS/CTS-type scheme for LTE-LBT. Its transmitting phase includes 4-way handshaking: downlink RTS, uplink CTS, downlink data packet, and uplink ACK/NACK response. The time statistics are given by

$$\begin{aligned} T_{s,L} &= T_{L,\text{RTS}} + T_{L,\text{SIFS}} + T_{L,\text{CTS}} + T_{L,\text{SIFS}} + T_{P,L} \\ &\quad + T_{\text{Defer}} \end{aligned} \tag{32}$$

$$T_{c,L} = T_{L,\text{RTS}} + T_{L,\text{SIFS}} + T_{L,\text{CTS}} + T_{\text{Defer}}, \tag{33}$$

where $T_{L,\text{RTS}}$ and $T_{L,\text{CTS}}$ are the durations of RTS and CTS packets, respectively; $T_{L,\text{SIFS}}$ is the short handshaking delay (or LTE SIFS) between uplink transmission and downlink response, and we assume $T_{L,\text{SIFS}} = T_{\text{SIFS}}$.

The 2-way handshaking basic access scheme (the first setting) proposed above is consistent with the LAA LBT and HARQ-ACK guidelines provided in [5]. To our knowledge, the second setting – RTS/CTS-type LBT scheme has not been discussed in [5]. This scheme is proposed here for both theoretical and practical interest: it provides substantial performance enhancement because it can reduce the time-

$$T_{\text{ave}} = \prod_{i=1}^{N}(1-P_{b,i})\delta + \sum_{i=1}^{N} P_{s,i}\left(\prod_{\substack{j=1\\j\neq i}}^{N}(1-P_{b,i})\right)T_{s,i} + \sum_{i=1}^{N}(P_{b,i}-P_{s,i})\left(\prod_{\substack{j=1\\j\neq i}}^{N}(1-P_{b,i})\right)T_{c,i}$$
$$+ \sum_{i=1}^{N}\sum_{\substack{j=1\\j\neq i}}^{N} P_{b,i}P_{b,j}\left(\prod_{\substack{l=1\\l\neq i,j}}^{N}(1-P_{b,l})\right)\max(T_{c,i},T_{c,j}) + \cdots + \left(\prod_{i=1}^{N} P_{b,l}\right)\max(\{T_{c,i}\}_{i=1,\ldots,N}). \quad (28)$$

efficiency loss caused by collisions. Performance of both schemes will be evaluated in Section V.

V. Numerical Results

In this section, we provide both analytical and simulation results of the WLAN downlink and uplink transmissions in coexistence with LTE-LBT downlink transmission. We implement computer programming based on modified DCF MAC algorithms given in [15], and the Category-4 LBT algorithm described in Fig. 1 adopted from [5]. In our simulation, we define three global events: channel idle, successful transmission, and collision; and four local events for each WLAN and LTE node: channel idle, counter freezing (due to channel being busy), successful transmission, and collision. The simulation results were obtained by running for 1×10^5 time slots on each parameter setting. In each slot, each node updates its local event and a global tracker updates the global event. Finally, based on accumulated numbers of events, the statistics of time-efficiency throughput and channel access and collision probabilities are computed for each node. Every analytical curve shown in this section is accompanied by a simulation curve and validated.

The parameters used for analysis and simulation are listed in Table I, where the WLAN parameters were adopted from [7], [9], [15], [16]. The $T_{s,W}$ and $T_{c,W}$ can be computed from the parameters in Table I using a method in [13], [15]. Here, channel bit rate (CBR) $=100$ mega-bits per second (Mbps), assumed to be the same for both LTE and WLAN systems. Saturated traffic is assumed for all nodes. The spectrum sensing (aka. CCA) in both WLAN and LTE-LBT systems is assumed to be perfect (no hidden node problem, no false alarm or miss detection). We study the effects of basic access and RTS/CTS schemes for the WLAN system, and basic access and 4-way handshaking schemes for the LTE LBT.

First, we study the effect of the LTE-LBT cutoff stage setup, and let R_L increase from 0 to 8, when $n_L = n_{W_D} = 4$, $n_{W_U} = 20$, $R_D = R_U = 6$, $W_{0,D} = Z_L = 16$, and $W_{0,U} = 80$, with WLAN RTS/CTS access. Note that the case of R_L = 0 models the Category-3 LBT, and $R_L = 1, \ldots, 8$ models Category-4 LBT. Here, we set $W_{0,U} = 5W_{0,D}$ so that WLAN downlink has higher priority to access the channel than the uplink. The results on throughput and transmission probabilities are presented in Figs. 3 and 4, respectively. The analytical and simulation results are in close agreement. The results show that when R_L increases, each LTE eNB node decreases its own throughput and transmission probability, but the LTE and WLAN sum throughput increases.

TABLE I: LTE and WLAN Parameters Used for Simulation

LTE parameters

Parameter	Value
Packet payload duration $T_{P,L}$	2 ms
$T_{L,\text{RTS}}$ (= $T_{L,\text{CTS}}$)	10 μ s
$T_{L,\text{SIFS}}$	16 μ s
LBT defer period: T_{Defer} (=T_{DIFS})	34 μ s
LBT eCCA period: T_{eCCA} (=δ_W)	9 μ s

WLAN parameters

Parameter	Value
Packet payload duration:	1 ms
MAC and PHY headers	272 and 128 bits
T_{SIFS}	16 μ s
T_{DIFS}	34 μ s
Idle slot duration δ_W	9 μ s
Downlink: $W_{0,D}$, R_D	16, 6
Uplink: $W_{0,U}$, R_U	80, 6

Next, we check the effect of replacing some WLAN APs with an equal number of LTE eNBs, on the throughput of LTE and WLAN systems, respectively. In the first setting, we let $n_{W_U} = 20$, $n_L + n_{W_D} = 8$, and $Z_L = W_{0,D} = 16$, and show throughput results in Fig. 5 assuming WLAN basic access, and in Fig. 6 with WLAN RTS/CTS access, respectively. The LTE basic access scheme is assumed. As n_L increases from 0 to 8 (with $n_L + n_{W_D} = 8$), the overall throughput of three types of transmissions increases from about 70 % to 74 % with WLAN basic access (constructive coexistence), but decreases from about 88 % to 78 % with WLAN RTS/CTS access (non-constructive coexistence). This demonstrates that the coexistence results critically depend on whether the original WLAN system has low efficiency (70 %, basic access) or high efficiency (88 %, RTS/CTS access).

In the second setting, we compare two cases: WLAN only with $n_{W_D} = 8, n_L = 0$; and four WLAN APs are replaced by LTE eNBs ($n_{W_D} = 4, n_L = 4$). We study the effect of CW size Z_0, and effect of LTE-LBT access methods (basic vs. RTS/CTS) on the throughput. We consider WLAN RTS/CTS

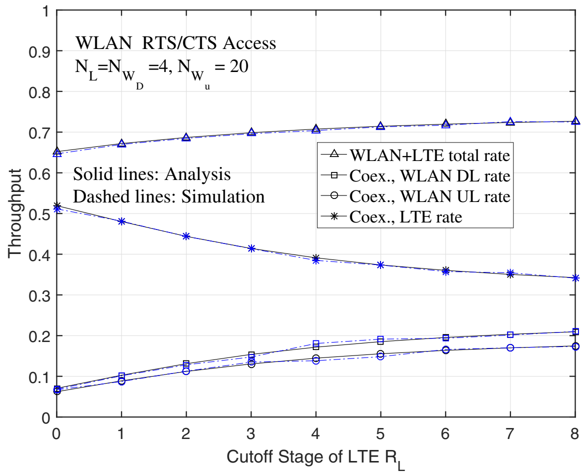

Fig. 3: Throughput of LTE and WLAN systems, when $n_L = n_{W_D} = 4$, $n_{W_U} = 20$, $R_D = R_U = 6$, $W_{0,D} = Z_L = 16$, and $W_{0,U} = 80$, with WLAN RTS/CTS access.

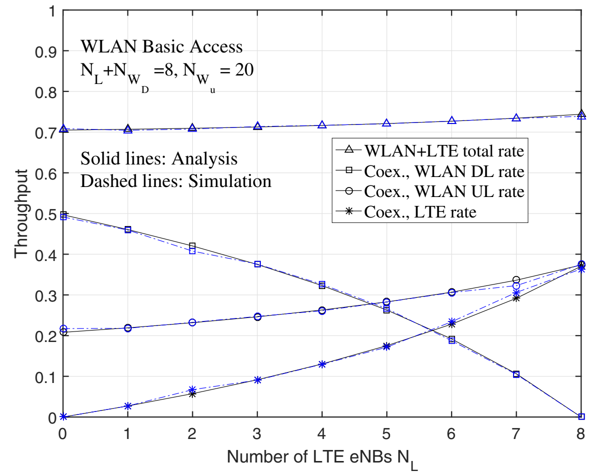

Fig. 5: Throughput of LTE and WLAN systems, when $n_L + n_{W_D} = 8$, $n_{W_U} = 20$, $R_D = R_U = R_L = 6$, $W_{0,D} = Z_L = 16$, and $W_{0,U} = 80$, with WLAN basic access.

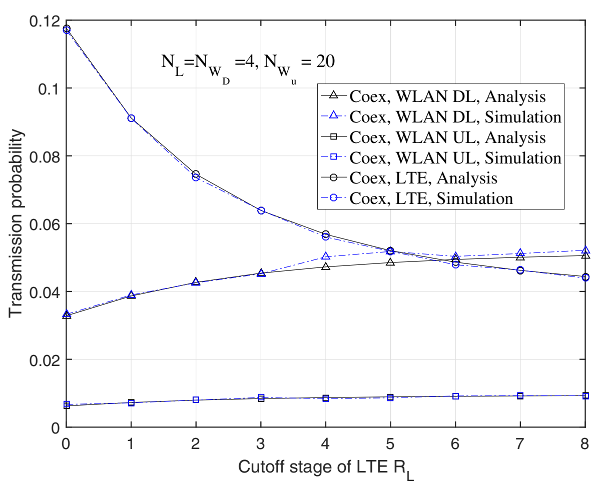

Fig. 4: Transmission (channel access) probabilities of LTE and WLAN systems, respectively.

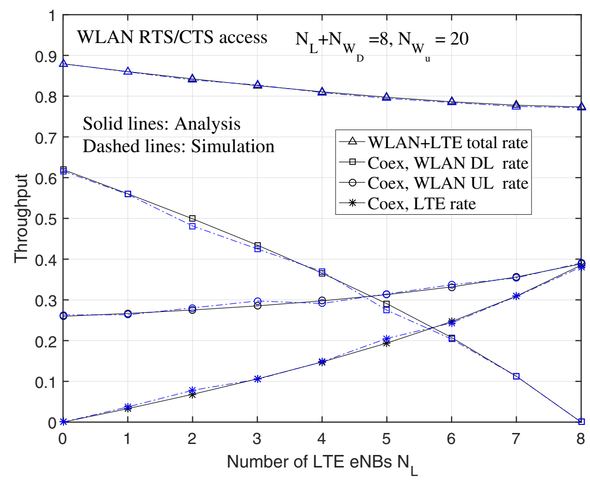

Fig. 6: Throughput of LTE and WLAN systems, with WLAN RTS/CTS access.

access, when $n_{W_U} = 20$, $R_U = R_D = R_L = 6$, $W_{0,D} = 16$, and $W_{0,U} = 80$. The results are provided in Fig. 7 assuming LTE basic access and in Fig. 8 assuming the proposed LTE-LBT 4-way handshaking channel access scheme (aka, LTE RTS/CTS-type access), respectively. It is observed that with LTE basic access scheme the coexistence sum throughput increases from about 70 % to 84 %, but is constantly worse than that of the original WLAN system (about 88 %). Fortunately, by using the LTE-LBT with our proposed RTS/CTS access, Fig. 8 shows that the coexistence sum rate (about 90 % $\sim$ 92 %) is consistently better than that of the original WLAN system. AT $Z_0 \approx 16$, the WLAN and LTE systems have approximately equal normalized throughput.

VI. Conclusion

In this paper, we have studied MAC-layer performance of LTE-LBT downlink coexisting with WLAN downlink and uplink transmissions. We have provided a flexible analytical approach to evaluate the transmission probability, collision probability and time-efficiency throughput. Since future co-existence scenarios will likely involve multiple systems, to support the related performance analysis, we have generalized the analysis result to multiple transmission types (more than three). We have implemented LTE and WLAN MAC algorithm programming and extensive computer simulation, and simulation results have verified the validity of our analysis result. Effects of the LBT cutoff stage, CW sizes, and handshaking access schemes have been evaluated. Regarding the fair co-existence between LTE and WLAN systems, our work shows

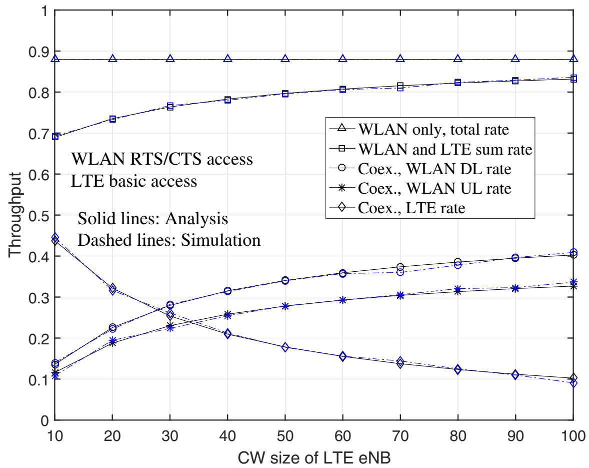

Fig. 7: Throughput of LTE-LBT and WLAN systems, when $R_L = 6$ with WLAN RTS/CTS access.

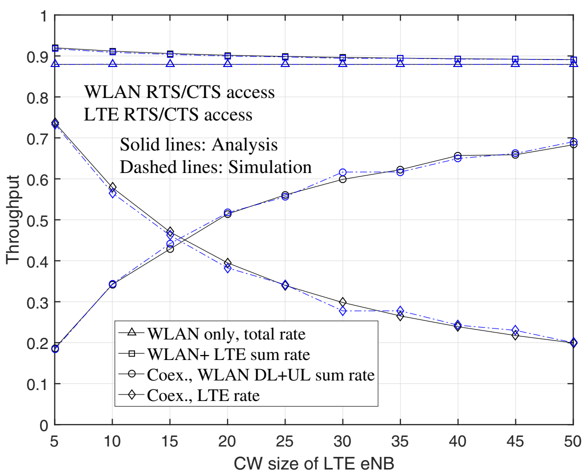

Fig. 8: Throughput of LTE-LBT and WLAN systems, when $R_L = 6$ and both WLAN and LTE systems use RTS/CTS access schemes.

that when the WLAN system uses RTS/CTS with saturated downlink and uplink traffic, replacing WLAN nodes with an equal number of LTE-LBT nodes may substantially reduce the overall throughput. To enhance the overall coexistence throughput, we have proposed an RTS/CTS type LBT channel access scheme and illustrated its competitive performance. In summary, the coexistence results depend heavily on the proper selection of handshaking schemes (basic or RTS/CTS access) and MAC parameters of both LTE-LBT and WLAN systems. Our results demonstrate that achieving satisfactory coexistence of LTE and WLAN systems is a non-trivial task, and additional research is needed. Perfect channel sensing is considered in this paper. In future work, the effect of channel sensing threshold and sensing errors will be studied, and measurement and testing procedure will be implemented to further validate the analytical and simulation results.

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