Analytical Model for Coexistence Performance Evaluation of WiFi and LTE Licensed-Assisted Access to Unlicensed Spectrum

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Abstract —LTE Licensed-Assisted Access (LAA) to unlicensed spectrum has been considered as an effective complement in offloading growing traffic since its emergence at 3GPP. Since 2015, 3GPP has launched standardization to develop LAA as a key technology for LTE-Advanced unlicensed spectrum deployment in Rel-13. In this paper, an analytical model is built for the performance evaluation of typical coexistence of Licensed-Assisted Access (LAA) LTE and WiFi IEEE 802.11. Assuming that LAA eNode-B performs Channel Clear Assessment (CCA) in a manner similar to Carrier Sense Multiple Access (CSMA) of WiFi, we use a two dimensional Markov chain to help analyzing not only the affected performance of WiFi but also the relation between the joint system performance and LAA maximum transmission time. After analytical analysis and simulations, it is shown that under certain system configuration joint system performance is approximately inversely proportional to a monomial of the maximum LAA transmission time.

Index Terms—Licensed-assisted access, Long Term Evolution in unlicensed spectrum, WiFi IEEE 802.11, coexistence performance evaluation

I. INTRODUCTION

As a LTE-based evolution at unlicensed spectrum, LAA tries to inherit the feature used at licensed spectrum which also reduces the standardization effort. However, given severe coexistence problems, series of access mechanisms have to be adopted by LAA to ensure fair performance of other operators and wireless technologies operating in the unlicensed spectrum. As a result, several mechanisms have been introduced in standardization for LAA in order to perform contention-based channel access. Just as the way WiFi does it, LAA access schemes are also equipped with contention window and exponential backoff according to latest standardizations [1]. Among these schemes adopted, use of Listen-Before-Talk (LBT) is of most importance for fair and friendly coexistence of LAA with other operators and technologies. It is recommended in [1] that a Category 4 LBT mechanism is the baseline at least for LAA downlink transmission bursts.

Many have looked into coexistence problems between LAA and WiFi 802.11 technology in recent literatures, but none of them are able to provide analytical models for how much difference can be made by LAA when evaluating the coexistence system performances. Reference [2] presents a detailed overview of the impact of unlicensed spectrum operation on the LTE physical layer architecture. Inter-system interference between LTE and WLAN operating in the same unlicensed spectrum is analyzed either through continuum field theories in [3] or by purely experimental analysis in [4]. A proportional fair allocation scheme aiming at ensuring fair coexistence between LTE-Unlicensed and WiFi is proposed in [5]. Lien et al. first propose the random access approach of LAA uplink transmission in [6], where advantages of introducing random access to LAA uplink have been fully discussed. However, Lien's optimum performance can only be achieved through adjusting the number of service UE, which inevitably introduces additional complexity to the system. Uplink random access does no better job than scheduled access in settling inefficiency matters, since the number of service UE is out of control in most cases. Thus we come up with an integrated UL radio access scheme which is neither rigid nor disordered on the whole. Reference [7] proposes a dynamic UL radio access selection scheme (DRAS) in which the LAA network employs two UL radio access approaches simultaneously, and analytically derive system utility with DRAS, solving the problem raised and discussed in [6].

This paper provides an accurate yet simple analytical model for joint system performance evaluation considering coexistence between LAA LTE and WiFi IEEE 802.11. The results of the analysis go far in guiding joint system configuration. This paper concentrates on the stationary throughput analysis of WiFi and the joint system of LAA/WiFi in the assumption of ideal channel conditions and finite number of terminals. By employing a two dimensional Markov chain analysis revised and extended from [8], we consider that both LAA and WiFi access are equipped with an $(m + 1)$-stage exponential backoff. As proven by comparison with simulation, our

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analytical model leads to accurate results. The key approximation that enables our model is the assumption of constant and independent collision probability of a packet transmitted by either eNode-B or WiFi station, regardless of any retransmission suffered.

This paper is outlined as follows. In Section II we build up an analytical model employing a two dimensional Markov chain. In Section III we compute WiFi stationary throughput and further the joint throughput of the coexisting system. We provide validation of the accuracy of the model by comparing the analytical results with those obtained by simulations in Section IV. Section V concludes this paper.

II. System Model

Category 4 LBT scheme with Channel Clear Assessment (CCA) has been introduced in [1] for LAA to ensure coexistence with WiFi. The scheme is almost identical to Carrier Sense Multiple Access (CSMA) adopted by WiFi 802.11 except that *for LAA it is the eNode-B (eNB) who detects the channel occupancy rather than the User Equipment (UE).* Additionally, the maximum transmission time T_l is introduced so that LTE do not keep the channel too long to starve WiFi. Thus when LAA and WiFi are deployed together, eNode-Bs and WiFi stations contend among each other for channel access in a similar manner. In what follows in this paper, the importance of the factor T_l in affecting the coexistence performance of WiFi and LAA is discussed.

A. Two Dimensional Markov Chain Analysis for both LAA and WiFi

Consider a fixed number of N contending stations (referred to as either eNB or WiFi station in the rest of this paper), consisting of N_l LAA eNBs and N_w WiFi stations. In steady-state, each station has an immediate packet for transmission, after the completion of each successful transmission. Yet each packet has to wait for a random backoff time according to either LBT CCA or CSMA. The stationary probability that each station transmits a packet in a random slot time is referred to as τ in this paper. To help understanding, network topology and interference scenario considered in our analysis are depicted in Fig. 1.

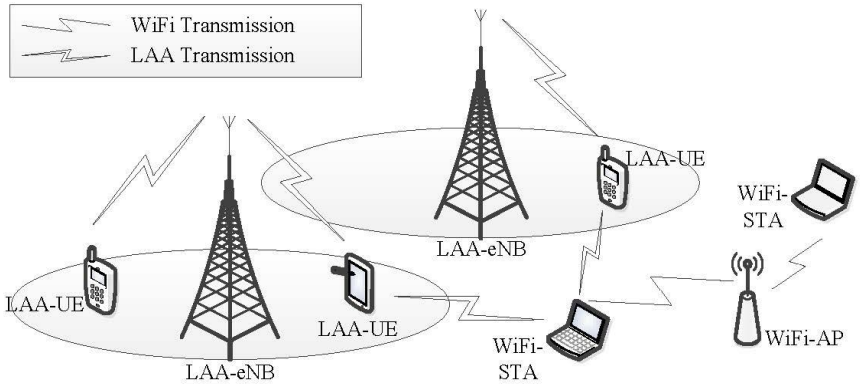

Fig. 1. Network topology and interference scenario

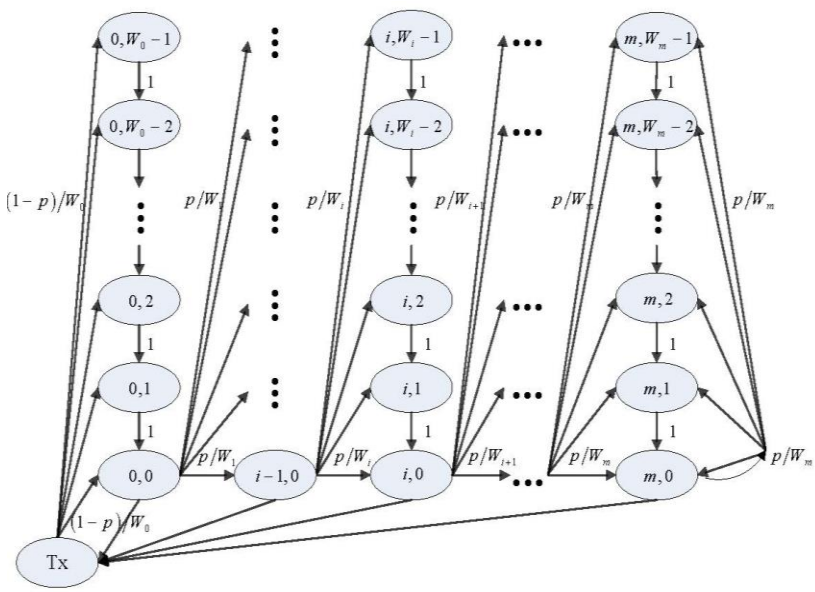

Fig. 2. A two dimensional markov chain for LAA eNBs and WiFi stations

In [8], Bianchi has utilized such Markov analysis in order to derive correlation between WiFi optimal performance and contention window factor. However in this paper we modify the corresponding Markov chain to fit in our analysis for LAA LBT process.

Let $w(t)$ be the stochastic process representing the backoff counter for a given station. Define $W = CW_{\min}$ and $CW_{\max} = 2^m W$, in which $CW_{\min}$ is the minimum contention window and m is the maximum backoff stage number. Thus $W_i = 2^i W$, where i stands for backoff stage. Let $s(t)$ be the stochastic process representing the backoff stage $(0,\cdots,m)$ of the station. We employ a two dimensional Markov chain representing the bi-dimensional stochastic process $\{s(t), w(t)\}$, as depicted in Fig. 2.

According to this Markov chain, we can obtain the only non-null one-step transmission probabilities [8], [9].

$$\begin{cases} P\{i,k \mid i,k+1\} = 1, k \in (0, W_i - 2), i \in (0,m) \\ P\{0,k \mid i,0\} = 1 - p/W_0, k \in (0, W_0 - 1), i \in (0,m) \\ P\{i,k \mid i-1,0\} = p/W_i, k \in (0, W_i - 1), i \in (1,m) \\ P\{m,k \mid m,0\} = p/W_m, k \in (0, W_m - 1) \end{cases} \tag{1}$$

in which p is the probability of a collision seen by a packet being transmitted on the channel. It is assumed to be a constant value standing for *conditional collision probability*.

Furthermore, it is easy to find a closed-form solution for this Markov chain. It is applicable for both LAA eNBs and WiFi stations as follows. It's necessary that we let $p_{i,k} = \lim_{t\to\infty} P\{w(t) = i, b(t) = k\}, i \in (0,m)$. The closed-form solution for the Markov chain can be expressed by:

$$\begin{cases} p_{i,k} = \dfrac{W_i - k}{W_i} p_{i,0}, i \in (0,m), k \in (0, W_i - 1) \\ p_{i,0} = p^i p_{0,0}, i \in (0,m) \\ p_{m,0} = \dfrac{p^m}{1-p} p_{0,0} \\ p_{0,0} = \dfrac{2(1-2p)(1-p)}{(1-2p)(W+1) + pW\left(1-(2p)^m\right)} \end{cases} \tag{2}$$

With such solution, we can analytically obtain a bunch of key parameters in the model we built. One of the parameters is the stationary probability τ that each station transmits a packet. Thus in a randomly chosen time slot, τ can be expressed as

$$\tau = \sum_{i=0}^{m} p_{i,0} = \frac{2(1-2p)(1-p)}{(1-2p)(W+1) + pW\left(1-(2p)^m\right)} \tag{3}$$

Next, we shall analytically derive the probabilities of the four possible events that may happen in the coexistence transmission scenarios.

B. Probabilities of the Possible Events

By studying the events that can occur within a randomly chosen slot time, we obtain the probabilities of occurrence of these events as function of τ in (4). Note that the four types of status are *Idle*, *Collision*, *WiFi successful transmission* and *LAA successful transmission*, respectively.

$$\begin{cases} P_w = N_w \tau (1-\tau)^{N_w + N_l - 1} \\ P_l = N_l \tau (1-\tau)^{N_w + N_l - 1} \\ P_{idle} = (1-\tau)^{N_w + N_l} \\ P_e = 1 - (P_{idle} + P_l + P_w) \end{cases} \tag{4}$$

in which P_w represents the occurrence probability that one and only one of the WiFi stations transmits in a random time slot and P_l correspondingly represents the probability that one and only one of the LAA eNBs transmits. Besides, P_{idle} and P_c represent the respective probabilities that a randomly chosen time slot is empty or sees a packet collision. Note that a collision is assumed to happen when more than one transmission occurs at the same time.

We assume that LAA and WiFi have the same time-slot length configuration, referred to as σ. We also assume that with a same occurrence probability P_c, every collision lasts for the same time duration T_c. Further, we use T_w and T_l to represent the maximum allowed time durations that one transmission can last for WiFi and LAA, respectively.

We are able to express the normalized total system throughput as follows. It equals to the ratio between average payload transmitted and average time spent. This definition has been discussed and agreed in several works including [8].

$$S = \frac{E[Payload]}{E[Time]} \tag{5}$$

In WiFi's case, payload can be calculated by multiplying the transmission probability of WiFi system and the expected payload volume of every single transmission. Naturally, the normalized WiFi throughput can be obtained by:

$$S_w = \frac{P_w E[P]}{P_{idle}\sigma + P_w T_w + P_l T_l + P_c T_c} \tag{6}$$

in which $E[P]$ represents average packet size transmitted by WiFi. So far, we have built an analytical model for WiFi stationary throughput in the given coexistence scenario, with which we are able to further derive the optimal solution of the WiFi throughput under interferences from LAA.

III. Throughput Analysis

With the analytical model given above, it is convenient to determine the maximum stationary throughput of WiFi. We rearrange (6) to obtain

$$S_w = \frac{E[P]}{\dfrac{P_{idle}}{P_w}\sigma + T_w + \dfrac{N_l}{N_w} T_l + \dfrac{P_c}{P_w} T_c} \tag{7}$$

In order to make full use of (7), we construct $A = E[P]/S_w, R = N_l/N_w$.

For better usage of *A*, we can develop it into:

$$A = \frac{P_{idle}\sigma}{P_w} + T_w + RT_l + \frac{P_c T_c}{P_w} \tag{8}$$

After further developing (8), we obtain:

$$A = \left[\left(\frac{T_c}{\sigma} - 1\right)P_c + 1\right]\sigma \Big/ P_w + RT_l + T_w - (1+R)\sigma \tag{9}$$

It needs to be noted here that, according to (9), S_w gets maximum value when *A* gets minimal value since σ and T_c are both constant values.

We continue to construct another tool parameter *B:*

$$B = \left[\left(\frac{Tc}{\sigma} - 1\right)P_c + 1\right]\sigma \Big/ P_w \tag{10}$$

Obviously, maximum S_w is determined by T_w , T_l , *R* and *B*.

We can observe that among the factors above, T_w is determined by WiFi transmission configuration and it has been assumed to be a known number. On the contrary, both T_l and *R* imply impact from LAA. They are either determined by system configuration or carried in system information. In order to find the affected maximum WiFi throughput, the optimal solution of *B* is of the greatest importance.

A. Optimum of B

After deforming (10), we obtain

$$B = \frac{1}{N_w}\left[\left(1-T_c^*\right)\frac{1-\tau}{\tau} + T_c^* \frac{1}{(1-\tau)^{N-1} - (1-\tau)^N} + N\left(1-T_c^*\right)\right] \tag{11}$$

in which $T_c^* = T_c/\sigma$ can be considered as the normalized collision time or the number of slots that a collision occupies.

Taking the derivative of (11) with respect to τ , and imposing it equal to zero, we obtain, after simplifications, the following equation

$$\left(T_c^* - 1\right)(1-\tau)^N + T_c^*\left(N\tau - 1\right) = 0 \tag{12}$$

Typically, we use the following approximation according to the McLaurin expansion,

$$(1-\tau)^N \approx 1 - N\tau + \frac{N(N-1)}{2}\tau^2 \tag{13}$$

By substituting (13) into (12), we obtain a rather simple quadratic equation

$$\frac{N(N-1)}{2} \bullet \left(T_c^* - 1\right)\tau^2 + N\tau - 1 = 0 \tag{14}$$

Thus we can derive the optimal $\tau = \tau^*$ that helps *B* get minimal value so that with known T_w, *T* and *R*, *A* gets minimal value at the same time with *B*. Further, optimal affected WiFi performance can be achieved when:

$$\tau^* = \frac{\sqrt{1 + 2\left(T_c^* - 1\right)(N-1)/N} - 1}{\left(T_c^* - 1\right)(N-1)} \tag{15}$$

B. Joint Performance

Corresponding to (6), LAA performance can be expressed as

$$S_l = \frac{P_l E[D_l]}{P_{idle}\sigma + P_w T_w + P_l T_l + P_c T_c} \tag{16}$$

which equals to

$$S_l = \frac{P_l E[D_l]}{P_w E[P]} \bullet S_w \tag{17}$$

in which $E[D_l]$ represents the average data transmitted by LAA within the duration of T_l . That is $E[D_l] = T_l E[R_l]$, where $E[R_l]$ stands for the average LAA transmission rate.

Substituting $A = E[P]/S_w, R = N_l/N_w$ into (17), we have:

$$S_l = \frac{RT_l E[R_l]}{A} \tag{18}$$

Under such circumstances, normalized joint stationary throughput of the heterogeneous system can be written as

$$S = \frac{N_l}{N} S_l + \frac{N_w}{N} S_w = \frac{N_l R T_l E[R_l] + N_w E[P]}{AN} \tag{19}$$

Because the transmissions of WiFi and LAA are statistically

After some simplifications, we easily obtain

$$S = \frac{N_l R T_l E[R_l] + N_w E[P]}{N\left[B + RT_l - (1+R)\sigma + T_w\right]} \tag{20}$$

In order to find the direct relation between *S* and T_l , we use the help of constructing *C*.

$$C = \frac{B - (1+R)\sigma + T_w}{R} \tag{21}$$

Reason for constructing *C* lies in that, *B* and *R* are known numbers under certain system estimation, which makes *C* also a known number.

With *C* substituted into (20), we obtain the following function that determines the key relation between *S* and T_l .

$$S = \frac{N_w E[P]/NR - CN_l E[R_l]/N}{T_l + C} + N_l E[R_l]/N \tag{22}$$

in which it informs that given known numbers N_w , N_l , *R*, *C*, $E[R_l]$ and $E[P]$, joint throughput *S* is inversely

proportional to a monomial of LAA maximum transmission duration T_l.

So far through a simple analytical model, we have finished analyzing joint performance brought by LAA and WiFi when typical coexistence conditions are considered. The accuracy validation of the results is in Section IV.

IV. Simulation Results

We conduct a series of simulations to evaluate WiFi optimum throughput and joint system throughput using the Matlab LTE simulation platform. Some of the key simulation parameters are listed in Table I. It should be noted that, cross-carrier scheduling is assumed in our simulations to prevent failure of UL grant that owes to LBT failure.

As depicted in Fig. 3, throughput curves of different network scales with different device number N are obtained by simulations. Through comparisons, the analytical calculated optimal τ values obtained by our solution are very close to the exact maximum τ values obtained by simulation. Additionally, a non-negligible difference in the estimate of the optimal value τ leads to similar result as the maximum value of the curves is rather smooth. To note that, the simulation max throughput which are the highest values of each corresponding curve, are recorded through link-level simulations.

TABLE I: Simulation Parameters

Cellular layout	Co-sited	Slot Time	9 μs
CWMin	31	Differ Time	18 μs
CWMax	1023	Center Frequency	5.2GHz
Resource batch length	4 ms	LAA-UE deployment	Uniform
Serving LAA-UE	20	UL resource batches	20
LAA-UE tx power	20 dBm	WiFi-STA tx power	15dBm

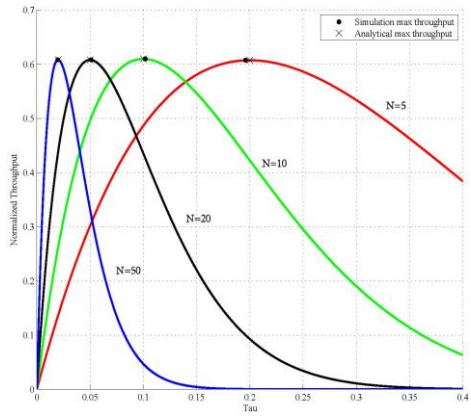

Fig. 3. Maximum normalized throughput versus Tau (Unit: ms).

On the other hand, Fig. 4 shows the average joint system throughputs under different T_l values by dark markers and the regression curve with a rather high R-squared level (0.9789). We can see from the figure that the normalized joint system throughput can be influenced by the LAA maximum allowed transmission time T_l. The regression curve also informs us that the joint system performance is approximately inversely proportional to the maximum LAA transmission time T_l. A high goodness of fitting informs us of a good validation for our analytical analysis in Section III.

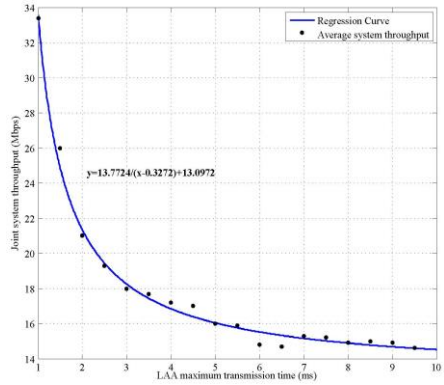

Fig. 4. LAA maximum transmission time (ms)

In conclusion, observations of the simulation results imply that the following statements are in perspective.

- Optimal affected performance of WiFi can be obtained when the transmission probability τ is properly adjusted, when typical coexistence conditions of LAA and WiFi IEEE 802.11 are considered.
- Given known numbers of contending stations in the coexisted system, transmission configurations of WiFi and average data capacities of WiFi and LAA slots, joint throughput S is inversely proportional to a monomial of the LAA maximum transmission duration T_l.

V. Conclusions and Future Works

In this paper, an analytical model for system performance evaluation considering typical coexistence of LAA LTE and WiFi IEEE 802.11 is built. Assuming that LAA eNBs perform CCA as the same manner to WiFi CSMA, we use a two dimensional Markov chain to help evaluate not only the affected performance of WiFi but also the relation between the joint system performance and LAA maximum transmission time. The results of this paper can be guidance in LAA/WiFi joint system configuration in the unlicensed spectrum. In future studies, we shall further exploit the impact drawn by each other between WiFi and LTE-LAA, digging deep into the access schemes of the two systems.

Appendix Notations

τ	Slot time
$p_{i,k}$	Probabilities of status i,k
T_l	Maximum allowed LAA transmission time
N_l	Number of LAA eNBs
N_w	Number of WiFi stations
p	Probability of collisions
P_w	Probability of WiFi transmission
P_l	Probability of LAA transmission
P_{idle}	Probability of empty slot
P_c	Probability of collision slot
S_w	Normalized WiFi system throughput
S_l	Normalized LAA system throughput
$A/B/C$	Mathematical constructions

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