The Listen before Talk based coexistence performance analysis over the unlicensed spectrum under multiple LTE small bases

Errong Pei, Deyue Meng, Junjie Jiang, Peng Zhang

***Abstract*—An analytical model is proposed to evaluate the Listen Before Talk (LBT) based coexistence scheme over the unlicensed spectrum under multiple LTE small bases (SBSs). The expressions of the occupancy time of the LTE/WiFi/access overhead and the collision probability is further derived based on the proposed model. The simulation results show that under multiple LTE SBSs the LBT based coexistence scheme is unfair for the WiFi system. Therefore, in order to protect the WiFi system the number of LTE SBSs and the length of the LTE frame should be carefully considered and designed.**

***Index Terms*—LTE unlicensed, LTE LAA, WiFi**

I. Introduction

Due to the sharply growth of data traffic in the mobile communication system, the more spectrums is required by the mobile communication system to increase their capacity. However, the licensed spectrum almost run out, and thus the mobile communication system, i.e. the LTE sysytem, is allowed use the unlicensed spectrum to expand its available spectrum. The LTE system that operates over the unlicensed spectrum is referred to as LTE-unlicensed (LTE-U) when used for standalone operation, and Licensed Assisted Access (LAA) when used for carrier aggregation, which is being standardized by the 3rd GPP [1, 10], and has recently attracted lots of attentions.

The dominant player is WiFi technology in the unlicensed spectrum, thus we mainly focus on the coexistence technology between WiFi and LTE systems. Presently there are two coexistence technologies between WiFi and LTE systems. The first is the duty cycle, in which according to a certain proportion the occupancy time of the LTE and WiFi systems is allocated[2]. The second is the Listen Before Talk (LBT) scheme, in which the LTE system is required to detect the its state before accessing the unlicensed spectrum. The scheme is thus a more fair and friend coexistence scheme. The coexistence scheme coexistence scenario where WiFi and multiple LTE SBSs being affiliated with different mobile operators simultaneously shares the unlicensed spectrum.

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To the best of our knowledge, the LBT based coexistence performance under multiple LTE SBSs is not still investigated so far.

When the backoff counter in a LTE small base (SBS), where LBT with random backoff mechanism is assumed to be installed, drops to 0 during a subframe, the data transmission in the LTE system has to be deferred until the starting of the next subframe because of the fact that a subframe is the minimal scheduling unit in the LTE system [1]. The duration between the moment at which the backoff counter drops down to 0 and the tail of the subframe is called the **suspending time**, during which the unlicensed channel cannot be accessed by LTE and WiFi systems, as shown in Fig. 1 (A). To the best of our knowledge, the suspending time is not invetigated so far.

As we well known, in the coexistence scenario, the collision between LTE and WiFi transmission can dramatically degrade the their throughput, in other word, the transmission collision can enormously affect the coexistence performance between WiFi and LTE. However, to the best of our knowledge, the transmission collision due to the backoff mechanisms of LTE SBSs and WiFi is still not studied in the LBT based coexistence performance evaluation so far.

An analytical model is proposed to assess the LBT based coexistence performance under multiple LTE SBSs in this paper, and based on the proposed analytical mode, and the expressions of the occupancy time of WiFi/LTE/the access overhead and the collision probability caused by the backoff mechanisms of LTE SBSs and WiFi is further derived, finally the performance of the occupancy time and the collision probability are deeply studied and assessed.

In this paper, the main contributions can be listed as follows:

(1) An analytical model is proposed to assess the LBT based coexistence performance under multiple LTE SBSs;

(2) The suspending time, which is defined as the duration between the moment at which the backoff counter of a LTE SBS drops down to 0 and the tail of the subframe, is first considered in the coexistence performance analysis;

(3) The backoff mechanisms of multiple SBSs and WiFi may result in the their transmission collision, which can severely influence the coexistence performance of WiFi and LTE systems. The collision probability is first considered in the coexistence performance analysis.

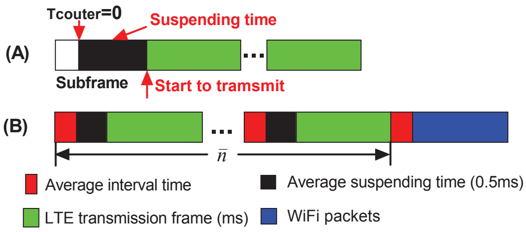

Fig. 1. The suspending time (A) and coexistence frame (B)

II. System Model

The multiple LTE SBSs is assumed to coexist with several WiFi access points (APs) over the unlicensed spectrum in this paper, and we also assumed that the LTE system has limitless traffic to use the unlicensed spectrum. As we well known, in WiFi networks, the different unlicensed channels may be allocated to different WiFi APs manually or automatically. Additionally, the APs operating over the same channel may also be separated by the spatial distance. Therefore, the considered model in this paper can still be boiled down to the model with several LTE SBSs and one WiFi AP. We further assume that the LTE SBSs belong to different operators, and thus they are non-coordinated and asynchronous. Finally, we also assume that the LAA Downlink transmission use the same backoff mechanism with fixed contention window size as WiFi systems.

Here, we also assume that when its backoff counter drops down to 0 during a subframe, LAA can use the method of transmitting dummy packet to hold the channel, and the dummy packet should last until the tail of the subframe.

III. The Analytical Model

Definition 1: *The time that cannot be used by the WiFi and LTE systems is called the* ***access overhead****, which includes Distributed Inter-frame Spacing (DIFS) and the suspending time as well as the backoff time.*

Theorem 1: *The average suspending time per LTE transmission is* $0.5ms$*, i.e.* ***Ts=0.5ms.***

Proof: It can be understand that the moment at which the backoff counter of each LTE SBS drops down to 0 is evenly distributed within a subframe (1ms), the suspending time from the moment to the starting of the next subframe thus is subjected to the even distribution in the interval [0 1], and further the average suspending time can be easily obtained, i.e. **Ts=0.5ms**. **[end of proof]**

Since the limitless traffic is assumed in the LTE system, LTE can always contend with WiFi users for the unlicensed channel. Therefore, we can infer that there is always saturated traffic (including WiFi and LTE traffic) over the coexistence channel. The literature [9] has showed that the instantaneous throughput temporarily increases over the saturation value, but ultimately it decreases and stabilizes to the saturation value in WiFi networks. We can conclude that the average time interval of the transmission of WiFi packets in the traffic-saturated case is also invariable. Therefore, though the sum of the LTE and WiFi throughput is not always invariable in the coexistence scenario, the time interval of the WiFi and LTE transmission can be inferred to be invariable. Thus we can define the transmission frame as follows.

Definition 2 (LTE Transmission frame): *The LTE transmission frame is defined as the sum of the transmission duration of LTE packets, their fixed time interval and the suspending time, as shown in Fig. 1 (B).*

Definition 3 (WiFi Transmission frame): *The WiFi transmission frame is defined as the sum of the transmission duration of WiFi packets and their fixed time interval, as shown in Fig. 1 (B).*

Definition 4 (Coexistence frame): *The coexistence frame of the WiFi and LTE systems is defined as a cycle, which includes* $\bar{n}$ *one WiFi transmission frame and LTE transmission frames, where* $\bar{n}$ *is the average number of LTE transmission frames per WiFi transmission frame, as shown in Fig. 1 (B).*

As discussed above, the time interval of the WiFi and LTE transmission is always changeless, thus we can calculate the average time interval (its unit is a time slot) in a coexistence frame as

$$\bar{d} = \frac{l}{\bar{n}+1} \tag{1}$$

where l is the fixed contention window size.

Based on the definition of the access overhead, we can calculate the access overhead in a coexistence frame as

$$\begin{aligned} T_{oh} &= \left(DIFS + \bar{d}\cdot slot\right) + \bar{n}\left(DIFS + \bar{d}\cdot slot + 0.5\right) \\ &= (\bar{n}+1)DIFS + l\cdot slot + 0.5\bar{n} \end{aligned} \tag{2}$$

where $slot$ is the time slot in the backoff mechanism.

The length of the coexistence frame can be described as

$$\bar{T} = \bar{n}T_{LTE} + T_{WiFi} + T_{oh} \tag{3}$$

where T_{LTE} is the length of LTE frames, and T_{WiFi} is the average length of WiFi packets.

Theorem 2: The average number of LTE frame per WiFi transmission can be calculated as:

$$\bar{n} = \frac{-b\lambda_{WiFi} + \sqrt{\left(b\lambda_{WiFi}\right)^2 + 4na\lambda_{WiFi}}}{2a\lambda_{WiFi}} \tag{4}$$

where $a = T_{LTE} + DIFS + 0.5$, $b = l\cdot slot + DIFS + T_{WiFi}$, λ_{WiFi} is the arrival rate of WiFi packets, and n is the number of LTE SBSs in the considered coexistence scenario.

Proof: Since both WiFi and LTE SBSs use the same backoff mechanism, the probability of each WiFi packet is thus the same as that of each LTE SBS accessing the unlicensed channel, and further the number of LTE frames per WiFi transmission completely depends on the ratio of the number of LTE SBSs to that of WiFi packets in the contention window, i.e.,

$$\bar{n} = \frac{n}{\lambda_{WiFi}\bar{T}} \tag{5}$$

The following equation with respect to $\bar{n}$ can be obtained by substituting (2) and (3) into (5) :

$$\begin{aligned} &\left(T_{WiFi} + DIFS + 0.5\right)\lambda_{WiFi}\bar{n}^2 \\ &\quad + (T_{LTE} + DIFS + l\cdot slot)\lambda_{WiFi}\bar{n} - n = 0 \end{aligned} \tag{6}$$

The formula method can be used to solve the quation (6), and the theorem 2 can be obtained. **[End of proof]**

The occupancy time of WiFi/LTE/access overhead can thus be described as, respectively,

$$R_{LTE}=\frac{\bar{n}T_{LTE}}{\bar{T}} \tag{7}$$

$$R_{WiFi}=\frac{T_{WiFi}}{\bar{T}} \tag{8}$$

$$R_{oh}=\frac{T_{oh}}{\bar{T}} \tag{9}$$

After their transmissions end, if the channel is idle for the duration of DIFS, immediately the LTE SBSs begin to perform backoff mechanism for the next transmission. It's possible for one LTE SBS to select the same backoff value as other LTE SBSs. The same backoff value can cause simultaneous transmission of more than one LTE SBS, which is called the transmission collision caused by the backoff mechanism. Because the backoff values are randomly chosen within the contention windon l, we can calculate the collision probability among LTE SBSs as follows

$$p_{LL}^{c}=1-\left(\frac{l-(\bar{n}-1)}{l}\right)^{\bar{n}} \tag{10}$$

Similarly, the transmission collision may also occur between WiFi and LTE due to the identical backoff value selected by them. The collision probability between WiFi and LTE can be calculated as

$$p_{WL}^{c}=1-\left(\frac{l-(\bar{n}-1)}{l}\right)^{\bar{n}M_L}\left(\frac{l-\bar{n}}{l}\right)^{(\lambda_{WiFi}\bar{T}-\bar{n}M_L)} \tag{11}$$

where $M_L=\lambda\cdot(T_{LTE}+0.5)$.

The collision probability among WiFi packets due to the above mentioned reason can be calculated as

$$p_{WW}^{c}=1-\frac{l}{l}\cdot\frac{l-1}{l}\cdots\frac{l-M+1}{l} \tag{12}$$

where $M=\lambda_{WiFi}\bar{T}-1$.

The total probability of the collision that occurred during the coexistence frame can thus be described as

$$p^{c}=p_{LL}^{c}+p_{WL}^{c}+p_{WW}^{c} \tag{13}$$

IV. Numerical results and Performance analysis

In the paper, we assumed that $DIFS=34us$, $l=15$, $slot=9us$, $T_{WiFi}=2.5ms$.

Since both the WiFi systems and the LAA downlink transmission use the same access protocol in the coexistence scenario, more LTE SBSs mean more chances to access the unlicensed spectrum, which can result in the growth of the LTE occupancy time (i.e., the sum of the occupancy time of all LTE SBSs) with the increase of the number of LTE SBSs. To the contrary, more access chances of the LTE system also mean less access chances of the WiFi system because of the time-sharing nature of the unlicensed spectrum. This can result in the decrease of the WiFi occupancy time with the increase of the number of LTE SBSs, as can be seen from Figure 2. More access chances of the LTE system also mean more access

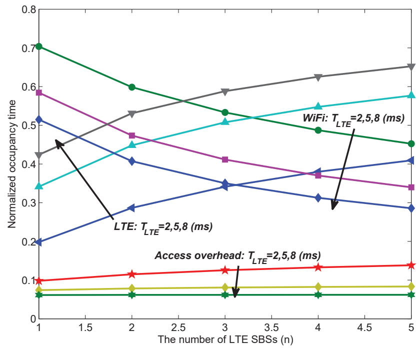

Fig. 2. The comparison of occupancy time: $\lambda_{WiFi}=0.2/ms$

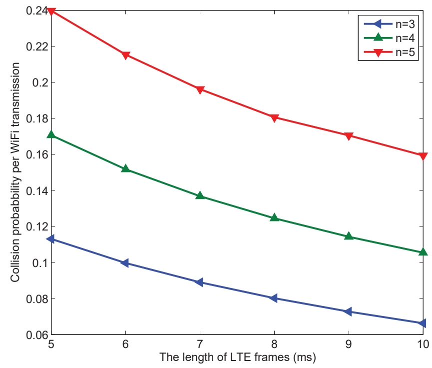

Fig. 3. The comparison of collision probability: $\lambda_{WiFi}=0.1/ms$

overhead (because of the increase of the suspending time), which can result in the growth of the access overhead.

It can be seen from Figure 2 that it isn't fair enough for the WiFi system in the coexistence scenario where there are multiple LTE SBSs since the WiFi occupancy time can be greatly reduced with the growth of the number of LTE SBSs and the length of the LTE frame, though LBT with random backoff value can provide the fairest access method among contending packets/frames.

The growth of the number of LTE SBSs can necessarily result in the growth of the collision probability (per WiFi transmission) because of the growth of the number of users contending for the unlicensed channel, as shown from Figure 3.

We can also seen from Figure 2 and Figure 3 that the growth of the length of the LTE frame can result in the growth of the LTE occupancy time and the reduction of the collision probability and the access overhead. However, since the unlicensed spectrum is its only access spectrum, the longer transmission frame can result in less WiFi occupancy time, which may be intolerant for some users with WiFi module only .

V. Conclusion

In this paper an analytical model is proposed to evaluate the LBT based coexistence performance in the scenario where there are multiple LTE SBSs. The simulation result showed that the growth of the number of LTE SBSs can bring the coexistence much harm in every respect (access overhead, the WiFi occupancy time, and collision probability) except in the LTE occupancy time, while the growth of the length of the LTE frame can bring the coexistence much benefit in every respect (access overhead, LTE occupancy time, and collision probability) except in the WiFi occupancy time. Therefore, in order to protect the WiFi system and guarantee unlicensed spectrum utilization, the number of LTE SBSs and the length of the LTE frame should be carefully designed.

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