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Performance Analysis of Listen Before Talk Based Coexistence Scheme Over the Unlicensed Spectrum in the Scenario With Multiple LTE Small Bases

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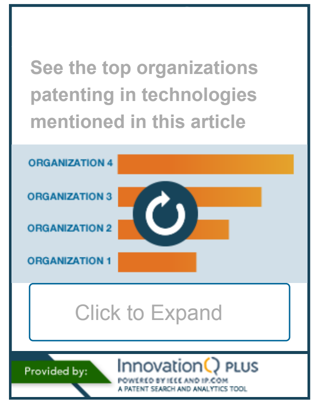

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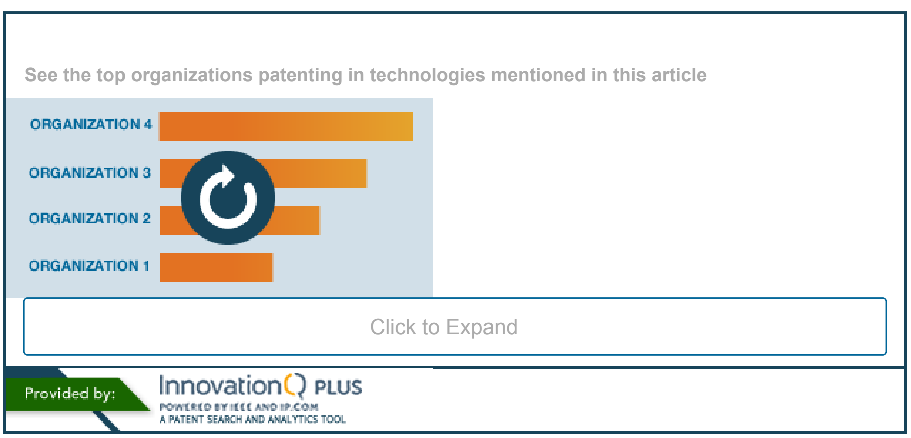

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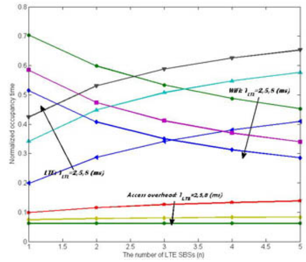

The comparison of the occupancy time of LTE and WiFi

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Abstract:

This paper proposes an analytical model to evaluate the performance of the listen before talk (LBT) based coexistence scheme in the scenario with multiple LTE small bases (SBSs) over the unlicensed spectrum. Based on the proposed model, we further derive the expressions of the occupancy time of the LTE/Wi-Fi/access overhead and the collision probability. It is shown from numerical results that the LBT-based coexistence scheme is not fair enough for the Wi-Fi system in the coexistence scenario with multiple LTE SBSs, and thus the number of LTE SBSs and the length of the LTE frame should be carefully designed to protect the Wi-Fi system.

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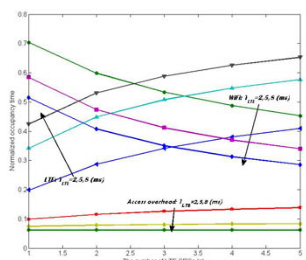

The comparison of the occupancy time of LTE and WiFi

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SECTION I.
Introduction

With the explosive growth of mobile data traffic, the mobile cellular network need more spectrums to boost their system capacity. However, the licensed spectrum is almost exhausted, and thus the unlicensed spectrum is being considered to use for the LTE system. The LTE system operating over the unlicensed spectrum is called 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], [7], and has recently attracted being standardized by the 3rd GPP [1], [7], and has recently attracted considerable attentions.

In the unlicensed spectrum, the dominant player is WiFi technology, thus the coexistence technology between LTE and WiFi systems is mainly investigated. Currently there exist two coexistence technologies between LTE and WiFi systems. One is the duty cycle, in which the occupancy time is allocated to the LTE and WiFi systems according to a certain proportion [2]. The other is the Listen Before Talk (LBT) scheme, in which the LTE system is designed to fairly and friendly coexist with the WiFi system. The scheme is similar to the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol in the WiFi system [5], [7], [10]–[11][12][13][14], for example, LBT with random backoff with a contention window of variable size in [3], and load based LBT in [4].

The majority of the existing works on LBT scheme mainly focus on the fair coexistence of one LTE small base (SBS) and one WiFi [5]–[6][7][8], [5], [7], [10]–[11][12][13][14]. However, there may exist multiple LTE SBSs belonging to different mobile operators in some coexistence scenarios, which simultaneously shares the unlicensed spectrum with the WiFi system.

To the best of our knowledge, the performance of the LBT based coexistence scheme in the scenario with multiple LTE SBSs is not still studied so far.

When the backoff counter in a LTE small base (SBS) where LBT with random backoff mechanism is installed drops to 0 during a subframe, the LTE transmission has to be deferred until the beginning of the next subframe since the minimal scheduling unit in the LTE system is a subframe [1]. The duration from the moment at which the backoff counter drops to 0 to the tail of the subframe is referred to as the **suspending time**, during which both LTE and WiFi cannot access the unlicensed channel, as shown in Fig. 1 (A). To the best of our knowledge, the suspending time is not studied so far.

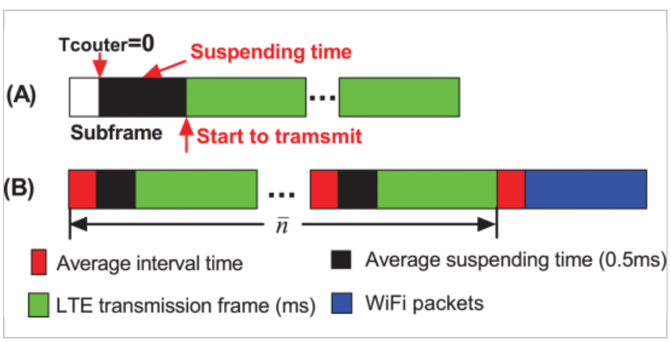

FIGURE 1.
The suspending time (A) and coexistence frame (B).

As we well known, the transmission collision can simultaneously degrade the throughput of LTE and WiFi systems in the coexistence scenario, that is to say, the transmission collision can greatly affect the coexistence performance. However, to the best of our knowledge, the transmission collision caused by the backoff mechanisms of LTE SBSs and WiFi is still not studied in the performance evaluation of the LBT based coexistence scheme so far.

In this paper, we provide an analytical model to evaluate the performance of the LBT based coexistence scheme in the scenario with multiple LTE SBSs, and the expressions of the occupancy time of multiple LTE SBSs, and the expressions of the occupancy time of LTE/WiFi/access overhead and the collision probability caused by the backoff mechanisms of LTE SBSs and WiFi are also derived based on

the proposed analytical model, finally the performance analysis with respect to the occupancy time and the collision probability are done.

The main contributions in this paper can be summarized as follows:

1. An analytical model is proposed to evaluate the performance of the LBT based coexistence scheme in the scenario with multiple LTE SBSs;
2. The suspending time, which is defined as the duration from the moment at which the backoff counter of a LTE SBS drops to 0 to the tail of the subframe, is first considered in the coexistence performance analysis;
3. The collision probability caused by the backoff mechanisms of multiple SBSs and WiFi, which can greatly affect the coexistence performance of WiFi and LTE systems, is first considered in the coexistence performance analysis.

SECTION II.
System Model

In this paper, we consider the scenario where multiple LTE SBSs coexist with multiple WiFi access points (APs) over the unlicensed spectrum, and it is assumed that the LTE system has unlimited traffic to use the unlicensed spectrum. As we well known, the different unlicensed channels may be allocated to different WiFi APs automatically or manually, and the APs operating over the same channel may also be isolated by the spatial distance. Therefore, the considered model can still be reduced to the model with multiple LTE SBSs and one WiFi AP. We further assume the LTE SBSs to belong to different operators, and thus they are asynchronous and non-coordinated. We also assume the LAA Downlink transmission and WiFi systems to use identical backoff mechanism with fixed contention window size.

Here, LAA is also assumed to use the way of transmitting dummy packet to hold the channel when its backoff counter drops to 0 during a subframe, and the dummy packet should continue until the tail of the subframe.

SECTION III.
The Analytical Model

Definition 1:
The time that cannot be exploited by the LTE and WiFi systems is referred to as the ***access overhead****, which includes the suspending time and Distributed Inter-frame Spacing (DIFS) 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 is not hard to understand that the moment at which the backoff counter of each LTE SBS drops to 0 is uniformly distributed within a subframe (1ms), the suspending time from the moment to the beginning of the next subframe thus obeys the uniform distribution in the interval [0 1], and further the average value of the suspending time can be easily obtained, i.e. **Ts=0.5ms**. **[end of proof]**

The LTE system is assumed to have infinite traffic, and thus it can always compete with WiFi users for the unlicensed channel. Therefore, it can be concluded that there is saturated traffic (including LTE and WiFi traffic) over the coexistence channel. It has been shown in the literature [9] that the instantaneous throughput temporarily increases over the saturation value, but ultimately it decreases and stabilizes to the saturation value in WiFi networks. It can thus be concluded that the average time interval of the transmission of WiFi packets in the traffic-saturated case is also constant. Therefore, though the sum of the LTE and WiFi throughput is not always constant in the coexistence scenario, the time interval of the LTE and WiFi transmission can be concluded to be constant. The transmission frame can thus be defined 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 LTE and WiFi systems is defined as a cycle, which includes $\bar n$ LTE transmission frames and one WiFi transmission frame, where $\bar n$ is the average number of LTE transmission frames per WiFi transmission frame, as shown in Fig. 1 (B).

As discussed earlier, the time interval of the LTE and WiFi transmission is always constant, thus the average time interval (its unit is a time slot) in a coexistence frame can be calculated by
$$\begin{equation} \bar d = \frac {l}{\bar n + 1} \end{equation}$$

where l is the fixed contention window size.

Based on the definition of the access overhead, the access overhead in a coexistence frame can thus be calculated as
$$\begin{align} {T_{oh}}=&\left ({ {DIFS +\bar d \cdot slot} }\right) + \bar n\left ({ {DIFS + \bar d \cdot slot + {\textstyle {0.5}}} }\right) \notag \\=& (\bar n+1)DIFS+l \cdot slot +0.5\bar n \end{align}$$

where slot is the time slot in the backoff mechanism.

The length of the coexistence frame can be described as
$$\begin{equation} \bar T = \bar n{T_{LTE}} + {T_{WiFi}} + {T_{oh}}$$

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

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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:

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

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

Proof:
Since both LTE SBSs and WiFi use the identical backoff mechanism, the probability of each LTE SBS accessing the unlicensed channel is thus identical to that of each WiFi packet, 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, namely,

$$\bar n=\frac {n}{{{\lambda _{WiFi}}\bar T}}$$

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Substituting (2) and (3) into (5) can obtain the following equation with respect to $\bar n$:

$$\begin{align}&\hspace {-2pc}\left ({ {{T_{WiFi}} + DIFS +0.5} }\right){\lambda _{WiFi}}{\bar n^{2}} \notag \\&\qquad +\,\left ({ {{T_{LTE}} + DIFS + l \cdot slot} }\right){\lambda _{WiFi}}\bar n - n = 0 \end{align}$$

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

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

$$\begin{align} {R_{LTE}}=&\frac {{{\bar nT_{LTE}}}}{\bar T} \\ {R_{WiFi}}=&\frac {{{T_{WiFi}}}}{\bar T} \\ {R_{oh}}=&\frac {{{T_{oh}}}}{\bar T} \end{align}$$

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After finishing their transmissions, if the channel is idle for the duration of DIFS, the LTE SBSs immediately start to perform backoff procedure for next transmission. It's possible for one LTE SBS to select the identical backoff value to other LTE SBSs. The identical backoff value can lead to concurrent transmission of more than one LTE SBS, which is referred to as the transmission collision caused by the backoff mechanism. Because the backoff value is randomly selected within the contention windon l , the collision probability among LTE SBSs can thus be calculated as

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

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

$$p_{WL}^{c} = 1 - {\left({\frac {{l - \left({ {\bar n - 1} }\right)}}{l}} }\right)^{\bar nM_{L}}}{\left({\frac {l - \bar n}{l}} }\right)^{{(\lambda _{WiFi}\bar T-\bar n M_{L})}}}\qquad$$

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where ${M_{L}} = \lambda \cdot \left({ {T_{LTE}} + 0.5 }\right)$.

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

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

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

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

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

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SECTION IV. Numerical Results and Performance Analysis

It's assumed that ${DIFS}=34us$, $l=15$, $slot=9us$, $T_{WiFi}=2.5ms$.

Since both LAA downlink transmission and WiFi systems use the identical access protocol in the coexistence scenario, more LTE SBSs mean more chances to access the unlicensed spectrum, which can lead to the increase of the LTE occupancy time (i.e., the sum of the occupancy time of all LTE SBSs) with the growth of the number of LTE SBSs. Contrarily, more access chances of the LTE system also mean less access chances of the WiFi system due to the time sharing nature of the unlicensed spectrum. This can lead to the decrease of the WiFi occupancy time with the growth of the number of LTE SBSs, as can be observed from Fig. 2. More access chances of the LTE system also mean more access overhead (due to the increase of the suspending time), which can lead to the increase of the access overhead.

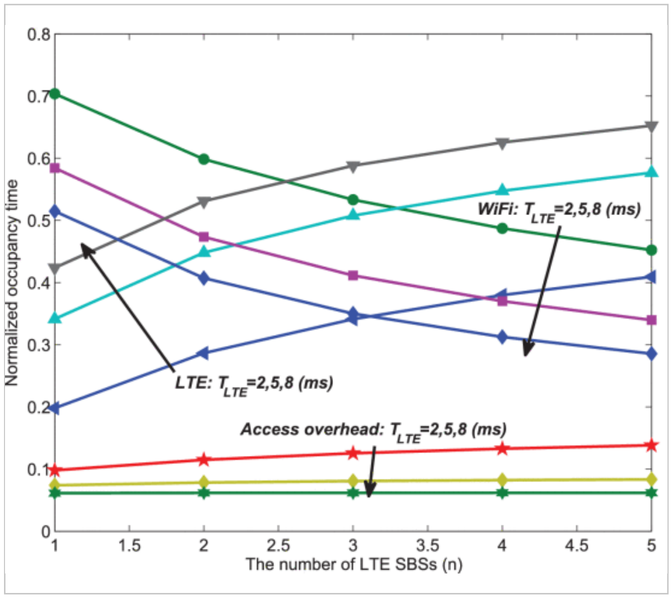

FIGURE 2.
The comparison of occupancy time: \lambda _{WiFi}=0.2/ms .

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

The increase of the number of LTE SBSs can necessarily lead to the increase of the collision probability (per WiFi transmission) due to the increase of the number of users contending for the unlicensed channel, as shown from Fig. 3.

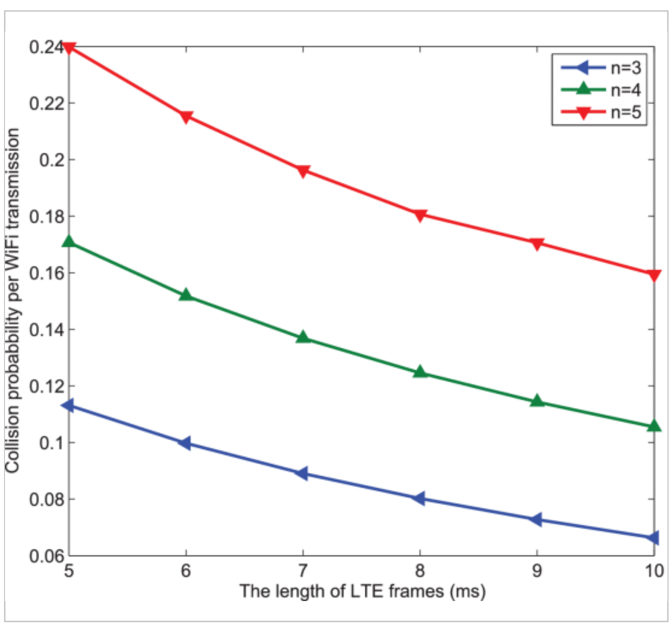

FIGURE 3.
The comparison of collision probability: \lambda _{WiFi}=0.1/ms .

We can also observed from Fig. 2 and Fig. 3 that the increase of the

We can also observed from Fig. 2 and Fig. 3 that the increase of the length of the LTE frame can lead to the increase of the LTE occupancy time and the decrease of the collision probability and the access overhead. However, the longer transmission frame can lead to less WiFi occupancy time, which may be intolerant for some users with WiFi module only because the unlicensed spectrum is its only access spectrum.

SECTION V. Conclusion

This paper proposes an analytical model to evaluate the performance of the LBT based coexistence scheme in the scenario with multiple LTE SBSs. It is shown that the increase of the number of LTE SBSs can bring much harm to the coexistence in every respect (the WiFi occupancy time, access overhead and collision probability) except in the LTE occupancy time, while the increase of the length of the LTE frame can bring much benefit to the existence in every respect (LTE occupancy time, access overhead and collision probability) except in the WiFi occupancy time. Therefore, the number of LTE SBSs and the length of the LTE frame should be carefully designed to protect the WiFi system and guarantee unlicensed spectrum utilization.