LBT with Adaptive Threshold for Coexistence of Cellular and WLAN in Unlicensed Spectrum

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***Abstract*—Coexistence of cellular networks and wireless local area network (WLAN) in unlicensed spectrum will be a vital application scenario in the future 5G network. Listen-before-talk (LBT) is one of the mechanisms to ensure a fair coexistence among various radio access networks. In this paper, we present a LBT algorithm with an adaptive threshold jointly considering the diverse traffic load conditions of cellular networks and the quality of service (QoS) metrics of user equipment (UE). The transmission procedure of a cellular base station (BS) is modeled utilizing M/GI/1 queuing system via queuing theory. Then the BS control the clear channel assessment (CCA) threshold according to the queue length to adapt to the diverse traffic loads under the condition of QoS guarantee. Simulation results show that the proposed algorithm achieves significant performance gain of the cellular network under the coexistence scenario on the premise of tolerable sacrifices on WLAN performance.**

***Index Terms*—cellular, WLAN, unlicensed spectrum, adaptive threshold, listen-before-talk (LBT).**

I. INTRODUCTION

Recent report predicts that mobile data traffic will hit a annual run rate of 367.2 exabytes by 2020. More specifically, a compound annual growth rate in the data traffic from 2015 to 2020 is 53% [1]. However, the limited spectrum resources are insufficient to meet the future needs of such a large mobile business. Many researchers believe it is a good solution to utilize the broad unlicensed spectrums in cellular networks [2]. As a result, the coexistence of cellular networks and wireless local area network (WLAN) in the unlicensed spectrum is a crucial application scenario in the future 5G network. Currently, there exists a few technologies in cellular network which could utilize unlicensed spectrums, including LTE in unlicensed spectrum (i.e., LTE-U) from LTE-U Forum [3] and licensed-assisted access using LTE (i.e., LAA-LTE) from 3GPP [4].

Unlike cellular networks previously deployed in the licensed spectrum, the unlicensed spectrum is open resource and can be used by any radio access network (RAN) as long as it is in accordance with the relevant provisions. Therefore, the coexistence issue of various RANs in unlicensed spectrum is in urgent demand to be resolved. Cellular networks must ensure a fair coexistence with incumbent WLAN in the unlicensed spectrum [5]-[7].

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The authors in [5] proposed a simple coexistence scheme which uses a concept of almost blank subframe, where the base station (BS) of the cellular network does not transmit any data in the blank subframe and thus WLAN access points (APs) can transmit data in the corresponding time without any interference from the cellular network. In [6], authors introduced the channel sensing adaptive transmission (CSAT) mechanism, in which the BS determines a transmission duty cycle for data transmissions based on the result of medium sensing. Several coexistence mechanisms for cellular BSs have been proposed in [7], including static muting, listen-before-talk (LBT), self-celar-to-send (self-CTS) and request-to-send/clear-to-send (RTS/CTS).

We can draw the original LBT scheme process from [8]. LBT mandates performing a clear channel assessment (CCA) with a fixed duration prior to a new transmission. If the channel is idle, the node will occupy the channel with limited duration. Otherwise, it will enter extended clear channel assessment (eCCA). [9] proposed a simple LBT scheme to adjust CCA threshold via the detected signal power. In [10], a LBT enhancement algorithm with contention window size adaptation for cellular networks was presented in order to achieve both channel access fairness and the QoS fairness. [11] proposed a fair LBT algorithm which jointly considers the total system throughput and the fairness between cellular networks and WLAN. Compared with the original LBT scheme, those modified LBT schemes have improved the performance of coexistence among cellular networks and WLAN to a certain extent. To our best knowledge, there is no consideration about the cellular network traffic load variation and the user QoS guarantee in the design of LBT scheme.

In this paper, we propose a LBT algorithm with adaptive threshold, which dynamically adjusts the CCA threshold by the queue length and adopts different transmission strategies for various traffic loads. Firstly, we utilize M/GI/1 queuing system to build the BS transmission model. Secondly, we introduce energy detect as key component of CCA while QoS metrics are defined as queue-length-bound violation probability and transmission-latency-bound violation probability. Finally, the BS then adjusts the CCA threshold according to the variation of the traffic loads under the condition of QoS guarantee. Simulation results show our proposed LBT algorithm achieves significant performance gain of the cellular network in user

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perceived throughput (UPT) and transmission latency under the coexistence scenario of cellular networks and WLAN at the expense of tolerable sacrifices on WLAN performance, especially in the heavy traffic load conditions.

The remainder of this paper is organized as follows. The system model is presented in Section II. LBT algorithm with adaptive threshold is introduced in Section III. Simulation evaluation and conclusions are given in Sections IV and V, respectively.

II. System Model

In this work, we only focus on the transmission situation of a cellular BS. In a heterogeneous network, a sector of one cell has N_C cellular BSs and N_W WLAN APs. A cellular BS transmission model can be summarized as a M/GI/1 queuing system in queuing theory as Fig. 1. The transmission model can be divided into four stages, respectively are file arrival stage, buffer queue stage, CCA/eCCA backoff stage and channel transmission stage.

According to the M/GI/1 queue system, the file arrival stage is a Poisson process with parameter λ, and the file arrival time interval follows an exponential distribution. Besides, it is assumed that the traffic model for each BS is FTP-3, where λ denotes the file arrival rate of the BS.

It will enter the buffer queue stage after files arriving at the BS. The file service is an opportunistic transmission in cellular networks, so it is necessary to set up a buffer to arrange arriving files. In this paper, we assume that the buffer size is infinite so that it can arrange infinite files. Moreover, first come first served (FCFS) algorithm is considered as the stack protocol in this work [12].

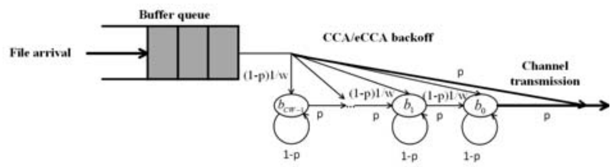

Fig. 1. Transmission model of a cellular BS

A file status transits from the buffer queue stage to the CCA/ECCA backoff stage when it is scheduled by the BS. At the beginning of this stage, the BS will first perform CCA with fixed duration by energy detection (elaborated in Section III). If the channel is idle, the BS will directly enter into the channel transmission stage; If not, the BS will enter eCCA. A backoff counter w for the file is firstly generated in the range $[0, CW-1]$ randomly fulfilling the uniform distribution, where CW means Contention Window for eCCA. That means the file has the same probability dropping into the state b_i, where $i \in [0, CW-1]$. In the eCCA backoff stage, the BS still shall perform a CCA to observe the channel availability. If the channel is checked as free, the backoff counter can be decreased by 1 (i.e. the file status moves from b_i to b_{i-1}). Otherwise, the backoff number maintains the same value since the channel is occupied by other BSs or APs. The transition probability of this process is assumed to be p, which is determined by many factors such as the number of competition BSs or Aps and the channel condition. In this contribution, p is also in relation to the buffer queue length. We assume that the transition probability p can be approximated by the channel occupancy rate or sensing result of a known cellular BS.

The channel transmission stage is equivalent to service stage in M/GI/1 queue system. Here we assume that files transmission time to be random variables R_n, which are independent identical distributed and independent of the file arrival process. The probability density function (PDF) is $g(r)$ while the mean is μ^{-1}. It is concluded that in this transmission model

$$\rho = \frac{\lambda}{\mu}, \tag{1}$$

where, μ is channel transmission rate. ρ denotes utilization coefficient of queuing system in which $\rho < 1$ shows a stable system.

III. LBT Algorithm with Adaptive Threshold

In this section, we will present the LBT algorithm with adaptive threshold in detail. The algorithm utilizes the buffer queue length to dynamically control the CCA threshold, which can help the cellular BS better adjust different traffic load. In this algorithm, we firstly introduce energy detection as one of the typical patterns of CCA. Then the QoS metrics are defined as queue-length-bound violation probability and transmission-latency-bound violation probability. Next, the CCA threshold will be concluded as a function of the buffer queue length on the premise of satisfying the QoS metrics. Finally, the algorithm flow is presented at the end of this section.

A. Energy Detection

There exists two typical patterns in CCA, which are clear channel assessment energy detection (CCA-ED) and clear channel assessment carrier sensing (CCA-CS). CCA-ED shall report a busy medium upon detecting any energy above the energy detection threshold while CCA-CS shall report a busy medium only upon the detection of a certain given signal. Among them, CCA-ED is adopted in this paper. We employ the energy detector for CCA-ED, which is described with the block diagram in Fig. 2 [13]. Specifically, a cellular BS first passes the sensed signal through the band-pass filter to remove the out-of-band noises. Then, the square-law device and integrator are applied to obtain the energy of the sensed signal with sampling time m within the certain observation interval T. We mainly focus on the output of the integrator, which is denoted by Y. The energy detector utilizes Y to test two hypotheses H_0 and H_1, where H_0 represents that the channel is idle and H_1 denotes the channel is busy. Moreover, Y follows the distributions as,

$$Y \sim \begin{cases} \chi^2_{2m}, & H_0(\text{the channel is idle}); \\ \chi^2_{2m}(2\gamma_r), & H_1(\text{the channel is occupied}), \end{cases} \tag{2}$$

where γ_r is the total signal-noise ratio of surrounding cellular BSs and WLAN APs to the cellular BS. χ^2_{2m} denotes the central chi-square distribution and $\chi^2_{2m}(2\gamma_r)$ represents the non-central chi-square distributions with the non-centrality parameter equal to $2\gamma_r$ [13].

In the above equations, $2m$ is the degree of freedoms. Then, we use a threshold ξ to decide the channel occupancy as follows,

$$Y \underset{H_0}{\overset{H_1}{\gtrless}} \xi\,. \tag{3}$$

When the decision is H_0, the BS could transmit data. Otherwise, the BS could not perform data transmission since the channel is occupied.

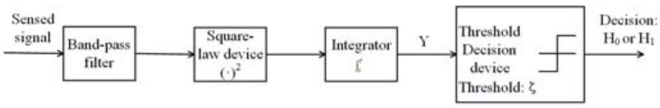

Fig. 2. Block diagram of an energy detector

B. QoS Metrics

Now we will introduce a few concepts: miss-detection probability P_m and false-alarm probability P_f. Their related definitions are as follows,

$$P_m = \Pr\{Y < \xi | H_1\}\,, \tag{4}$$

$$P_f = \Pr\{Y > \xi | H_0\}\,, \tag{5}$$

and they all can be assumed as a part of QoS metrics. Furthermore, CCA threshold rise with the increase of the buffer queue length, resulting in the raise of P_m and the decline of P_f, and vice versa.

In the discussion of the LBT algorithm with adaptive threshold, QoS metrics also include queue-length-bound violation probability P_{queue} and transmission-latency-bound violation probability P_{delay} which are defined by

$$P_{queue} = \Pr\{Q > Q_{th}\} \le P_{th1}, \tag{6}$$

$$P_{delay} = \Pr\{D > D_{th}\} \le P_{th2}, \tag{7}$$

where, Q denotes the buffer queue length and Q_{th} represents the buffer queue length threshold in (6). Similarly, D denotes the transmission latency and D_{th} represents the transmission latency threshold in (7).

C. Function between CCA Threshold and Queue Length

Our goal is to establish a function between the CCA threshold ξ and the buffer queue length Q in the LBT algorithm with adaptive threshold. Specifically, we require that the miss-detection probability and the false-alarm probability cannot exceed the specified threshold denoted by $\overline{P_m}$ and $\overline{P_f}$. In order to balance the channel access fairness between the cellular network and WLAN, we set the targeted average miss-detection probability and the targeted average false-alarm probability just equal to $\overline{P_m}$ and $\overline{P_f}$. Thus, we have

$$\overline{P_m} = \int_0^\infty P_m(Q) g(Q) dQ, \tag{8}$$

$$\overline{P_f} = \int_0^\infty P_f(Q) g(Q) dQ, \tag{9}$$

where $g(Q)$ denotes the PDF of the queue length distribution. $P_m(Q)$ expresses that P_m is the function of the buffer queue length Q while $P_f(Q)$ represents that P_f is the function of the buffer queue length Q.

The coexistence scenario of cellular networks and WLAN is mostly located in urban center or indoor environment, where there is no direct path for wireless signals. So it is assumed that Rayleigh fading model can be used in this paper. We can draw from [13] that

$$P_m + P_f + e^{-\frac{\xi}{2}} (\frac{\xi}{2})^m \sum_{k=0}^{m-2} \frac{1}{(m+k+1)!} (\frac{\xi\overline{\gamma}}{2(\overline{\gamma}+1)})^{k+1} = 1. \tag{10}$$

where $\overline{\gamma}$ denotes the average SNR. According to (10), the CCA threshold ξ can be expressed as a function between the miss-detection probability P_m and the false-alarm probability P_f.

According to [14], queue-length-bound violation probability P_{queue} and transmission-latency-bound violation probability P_{delay} of a dynamic queueing system are approximated by

$$P_{queue} = \Pr\{Q > q\} = e^{-\theta q}\,, \tag{11}$$

$$P_{delay} = \Pr\{D > d\} = \rho e^{-\mu\theta q}\,, \tag{12}$$

$$\mu^{-1} = \frac{\ln 2}{2^R - 1} \frac{p}{1-p} \int_0^\infty \frac{2^{\frac{1}{z}}}{z(2^{\frac{1}{z}} - 1 + \frac{p}{(2^R-1)(1-p)})^2} dz, \tag{13}$$

where R represents the channel transmission rate of other cellular BSs or WLAN APs. The parameter $\theta > 0$ describes the exponentially decaying speed of $\Pr\{Q > q\}$ as q increases, which is called the QoS exponent [14]. Accordingly, we can conclude the PDF $g(Q)$ of Q as

$$g(Q) = \theta e^{-\theta Q}. \tag{14}$$

Next, we will design the miss-detection probability P_m as a function of the buffer queue length Q and false-alarm probability P_f as a function of the buffer queue length Q, which are denoted by $P_m(Q)$ and $P_f(Q)$ respectively. We further require that control functions $P_m(Q)$ and $P_f(Q)$ have the following properties:(i) $P_m(Q)$ is a monotone increasing function of Q while $P_f(Q)$ is a monotone decreasing function of Q; (ii) $P_m(Q)$ and $P_f(Q)$ must be upper-bounded by 1.

We respectively choose linear functions and exponential functions to represent $P_m(Q)$ and $P_f(Q)$.

1) Linear Control Functions: We design the linear control functions $P_m(Q)$ and $P_f(Q)$ as follows,

$$P_m = \begin{cases} \frac{Q}{\varphi}, & 0 \le Q \le \varphi, \\ 1, & Q > \varphi, \end{cases} \tag{15}$$

$$P_f = \begin{cases} -\frac{Q}{\varphi}+1, & 0 \le Q \le \varphi, \\ 0, & Q > \varphi, \end{cases} \tag{16}$$

where $\varphi > 0$. Under those control functions, when the queue length is larger than or equal to φ, the cellular BS transmits data regardless of the current channel condition to decrease the queue-length-bound violation probability. When the queue length is equal to 0, the miss-detection probability and the false-alarm probability will also become 0 and 1, implying that the cellular BS does not attempt to occupy the channel in this case. If the queue length fall in the interval given by $(0, \varphi)$, the miss-detection probability and the false-alarm probability varies linearly to Q.

According to the (6), (7), (11), (12), we can draw

$$\theta \ge -\frac{1}{Q_{th}} \log(P_{th1}), \tag{17}$$

$$\theta \ge -\frac{1}{\mu D_{th}} \log(\frac{P_{th2}}{\rho}), \tag{18}$$

so

$$\theta \ge \max\left(-\frac{1}{Q_{th}} \log(P_{th1}), -\frac{1}{\mu D_{th}} \log(\frac{P_{th2}}{\rho})\right). \tag{19}$$

Then, we use the boundary value

$$\theta = \max\left(-\frac{1}{Q_{th}} \log(P_{th1}), -\frac{1}{\mu D_{th}} \log(\frac{P_{th2}}{\rho})\right), \tag{20}$$

as a guidance to design our control functions.

Plugging the (15) and (16) into the (8) and (9) respectively, we can obtain

$$\begin{aligned} \int_0^\infty P_m(Q)g(Q)dQ &= \int_0^\varphi \tfrac{\theta Q}{\varphi} e^{-\theta Q} dQ + \int_\varphi^\infty \theta e^{-\theta Q} dQ \\ &= \tfrac{1}{\theta\varphi}(1 - e^{-\theta\varphi}) = \overline{P_m}, \end{aligned} \tag{21}$$

$$\begin{aligned} \int_0^\infty P_f(Q)g(Q)dQ &= \int_0^\varphi (-\tfrac{Q}{\varphi}+1)\theta e^{-\theta Q} dQ \\ &= \tfrac{1}{\theta\varphi}(e^{-\theta\varphi} - 1) + 1 = \overline{P_f}. \end{aligned} \tag{22}$$

Solving this equation, we get the analytical expression of φ as follows,

$$\varphi = \frac{1}{\theta \overline{P_m}}[1 + \overline{P_m} w(-\frac{1}{\overline{P_m}} e^{-\frac{1}{\overline{P_m}}})], \tag{23}$$

$$\varphi = \frac{1}{\theta(1-\overline{P_f})}[1 + (1-\overline{P_f}) w(-\frac{1}{\overline{P_m}} e^{-\frac{1}{1-\overline{P_f}}})]. \tag{24}$$

In order to minimize the transmission delay and the queue length, we get

$$\begin{aligned} \varphi = \min(&\frac{1}{\theta \overline{P_m}}[1 + \overline{P_m} w(-\frac{1}{\overline{P_m}} e^{-\frac{1}{\overline{P_m}}})], \\ &\frac{1}{\theta(1-\overline{P_f})}[1 + (1-\overline{P_f}) w(-\frac{1}{\overline{P_m}} e^{-\frac{1}{1-\overline{P_f}}})]), \end{aligned} \tag{25}$$

where $w(\cdot)$ is the Lambert W function [15] which is known as the inverse function of $Z(W) = We^W$.

Applying φ into the (15) and (16), we get the linear control functions $P_m(Q)$ and $P_f(Q)$. Then Plugging those into (10), we can get the function between the CCA threshold ξ and the buffer queue length Q.

2) Exponential Control Functions: We design the exponential control functions $P_m(Q)$ and $P_f(Q)$as follows,

$$P_m(Q) = \begin{cases} 2^{\frac{Q}{\varphi}} - 1, & 0 \le Q \le \varphi, \\ 1, & Q > \varphi, \end{cases} \tag{26}$$

$$P_f(Q) = \begin{cases} -2^{\frac{Q}{\varphi}} + 2, & 0 \le Q \le \varphi, \\ 0, & Q > \varphi, \end{cases} \tag{27}$$

where $\varphi > 0$.

Next we can obtain the same value of θ with the linear control functions. Plugging the (26) and (27) into the (8) and (9) respectively, we can obtain

$$\begin{aligned} \int_0^\infty P_m(Q)g(Q)dQ &= \int_0^\varphi (2^{\frac{Q}{\varphi}} - 1)\theta e^{-\theta Q} dQ + \int_\varphi^\infty \theta e^{-\theta Q} dQ \\ &= 2e^{-\theta\varphi} + \tfrac{\theta\varphi - 2\theta\varphi e^{-\theta\varphi}}{\theta\varphi - \ln 2} - 1 = \overline{P_m}, \end{aligned} \tag{28}$$

$$\begin{aligned} \int_0^\infty P_f(Q)g(Q)dQ &= \int_0^\varphi (-2^{\frac{Q}{\varphi}} + 2)\theta e^{-\theta Q} dQ \\ &= \tfrac{\theta\varphi + (e^{-\theta\varphi} - 1)\ln 4}{\theta\varphi - \ln 2} = \overline{P_f}. \end{aligned} \tag{29}$$

Solving this equation, we get the analytical expression of φ as follows,

$$\varphi = \frac{1}{\theta \overline{P_m}}[(\overline{P_m}+1)\ln 2 + \overline{P_m} w(-\frac{2^{-\frac{1}{\overline{P_m}}} \ln 2}{\overline{P_m}})], \tag{30}$$

$$\varphi = \frac{1}{\theta(\overline{P_f}-1)}[(\overline{P_f}-2)\ln 2 + (\overline{P_f}-1) w(-\frac{2^{\frac{1}{\overline{P_f}-1}} \ln 2}{\overline{P_f}-1})]. \tag{31}$$

Also we draw

$$\begin{aligned} \varphi = \min(&\frac{1}{\theta \overline{P_m}}[(\overline{P_m}+1)\ln 2 + \overline{P_m} w(-\frac{2^{-\frac{1}{\overline{P_m}}} \ln 2}{\overline{P_m}})], \\ &\frac{1}{\theta(\overline{P_f}-1)}[(\overline{P_f}-2)\ln 2 + (\overline{P_f}-1) w(-\frac{2^{\frac{1}{\overline{P_f}-1}} \ln 2}{\overline{P_f}-1})]). \end{aligned} \tag{32}$$

Similarly, the function between the CCA threshold ξ and the buffer queue length Q can be obtained via the (10), (26), (27).

D. Algorithm Flow

The LBT algorithm with adaptive threshold can be elaborated on as the following steps in Table I.

Step 1: The BS sense the buffer queue length Q_* with fixed time intervals. Since it would be rather complex to set a short time interval, the sensing time interval can be fixed to a few seconds. Given a series of parameters including $\overline{\mathrm{P_m}}$, $\overline{\mathrm{P}_f}$, P_{th1}, P_{th2}, Q_{th}, D_{th} and $\overline{\gamma}$, CCA threshold could be calculated as ξ_* according to (10).

Step 2: When a file enter into the CCA/eCCA backoff stage, the BS would perform CCA utilizing the energy detector. The output of the integrator Y_* is compared with the ξ_* to test two hypotheses H_0 and H_1. H_0 represents idle channel to transmit data while H_1 denotes busy channel so that the BS will enter eCCA. The BS have to perform CCA until the backoff counter returns to zero, then it would perform data transmission.

TABLE I: Algorithm Flow

1. The BS would sense Q_*.
Given $\overline{P_m}$, $\overline{P_f}$, P_{th1}, P_{th2}, Q_{th}, D_{th}, $\overline{\gamma}$,
Calculated ξ_*.
2. Enter into CCA/eCCA backoff stage.
If $Y_* < \xi_*$, perform data transmission.
If $Y_* \geq \xi_*$, enter into eCCA,
performing CCA until the backoff counter returns to zero,
then enter into channel transmission stage.

IV. Simulation Evaluation

A. Simulation Environment

In our work, a comprehensive system level simulation of 3GPP LTE-A with small cell enhancement scenario 2a is performed by heterogeneous cellular network simulation platform. We consider a cellular network with 7 hexagonal cell sites and 3 sectors per site in an urban outdoor scenario. 4 cellular BSs and 4 WLAN APs are randomly dropped in each sector. In addition, we take $\overline{P_m} = \overline{P_f} = 0.1$, $P_{th1} = P_{th2} = 0.1$, $\overline{\gamma} = 15dB$, $Q_{th} = 500$, $D_{th} = 500ms$. Detailed simulation parameters are summarized in Table II according to 3GPP TR 36.889 [16].

TABLE II: Simulation Parameters

Parameter	Value
Urban outdoor scenario layout	Based on SCE #2a + unlicensed band; X=4, Y=1; 10 UEs per operator per carrier
Carrier frequency	5 GHz
System bandwidth	1 unlicensed carrier with 20 MHz
Maximum channel occupy time	4 ms for cellular BSs and 3 ms for WLAN APs
Traffic model	FTP Model 3 with 0.5 MB file size
File arrival rate	Chosen from [0.5,4] for cellular BSs and remains 0.5 for WLAN APs
Total BS TX power	18 dBm
Antenna configuration	2Tx-2Rx signal stream transmission
CCA backoff window	32 for cellular BSs and $[15, 1023]$ for WLAN APs
CCA slot length	24μs for cellular BSs and 9μs for WLAN APs
Channel coding	BCC
MCS	UP to 256 QAM
Link adaptation	Realistic for cellular BSs and rate control - minstrel algorithm for WLAN APs

B. Simulation Results

In this paper, we choose the original LBT scheme with the fixed CCA threshold of $-55dBm$ as the reference [16]. the proposed LBT algorithm with adaptive threshold is called the improved LBT algorithm in the following. The change of λ indicates traffic load variation of cellular BSs in the simulation.

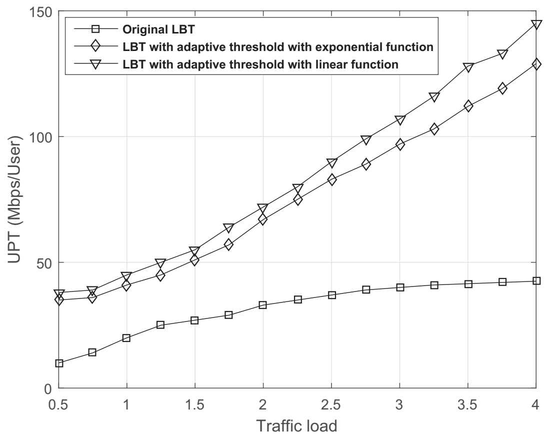

Fig. 3. User perceived throughput per cellular network UE

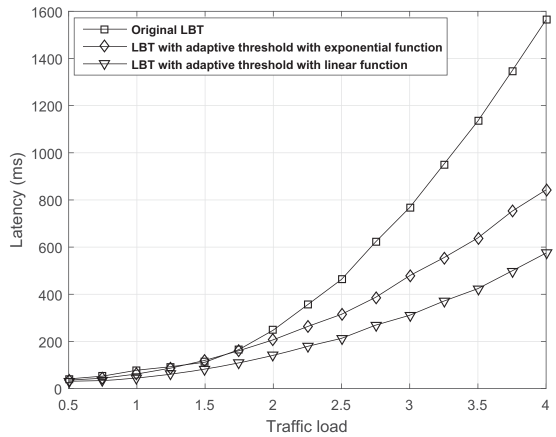

Fig. 4. Average transmission latency per cellular network UE

As can be seen from the Fig. 3 and Fig. 4, the improved LBT algorithm can achieve significant performance gain of the cellular network in UPT and transmission latency under the coexistence scenario of cellular networks and WLAN, compared with the original LBT scheme. This is because the improved LBT algorithm can utilize the channel more effectively under the same traffic load condition. Moreover, comparing with the improved LBT algorithm controlled by the exponential functions, the same LBT algorithm with the linear control functions has a better performance in UPT and transmission latency.

In addition, from the aspect of the improved LBT algorithm, the upward trend of throughput curve is more obvious and the upward trend of transmission delay curve is just the opposite with the increase of traffic load. When $\lambda = 1$, comparing with the original LBT scheme, the improved LBT algorithm gets the cellular network UPT improvements more than 80% while almost no clearly change in transmission delay. When $\lambda = 4$, the improved LBT algorithm gets the cellular network UPT improvements more than 150% while transmission delay improvements more than 50%. This shows that the growth of performance gain in the improved LBT algorithm rise with

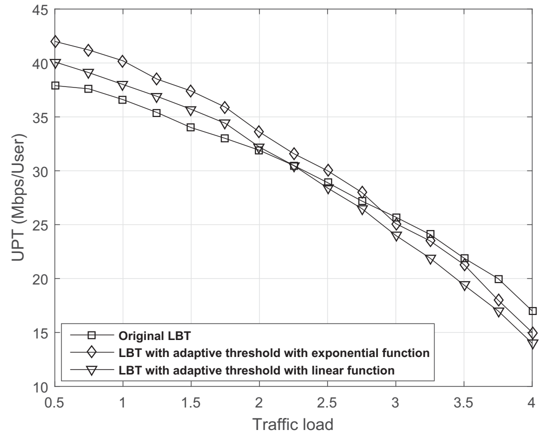

Fig. 5. User perceived throughput per WLAN UE

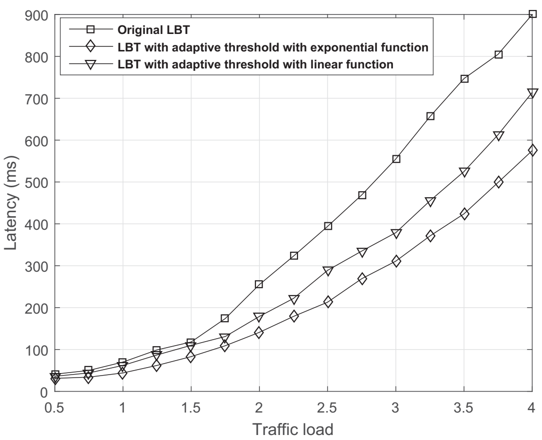

Fig. 6. Average transmission latency per WLAN UE

the increase of traffic load. On one hand, the buffer queue length of the cellular BS is short in light traffic load condition, adopting a smaller CCA threshold, reducing the channel access possibility of the BS, which is to take a relatively conservative transmission strategy; On the other hand, the buffer queue length of the cellular BS becomes long in heavy traffic load condition, adopting a larger CCA threshold, increasing the channel access possibility of the BS, which is to take a relatively aggressive transmission strategy. In a word, the CCA threshold rise with the increase of traffic load so that the BS can achieve maximum channel utilization.

Furthermore, we compare the Fig. 3 with Fig. 5 and Fig. 4 with Fig. 6 respectively. When $\lambda = 1$, comparing with the original LBT scheme, the improved LBT algorithm gets the cellular network UPT improvement more than 80% while almost no clearly improvements in transmission delay. WLAN gains UPT improvements about 10% while almost no distinctly improvements in transmission delay. When $\lambda = 4$, the improved LBT algorithm gets the cellular network UP-T improvements more than 150% while transmission delay improvements more than 50%. UPT of WLAN drops about 15% while transmission latency increases about 20%. This shows that the improved LBT algorithm can greatly enhance the performance of the cellular network at the expense of acceptable sacrifice on WLAN performance. Moreover, the improved LBT algorithm with two types of control functions can not both achieve greater performance gain on the cellular network and have smaller effect on WLAN performance. We need to make our trade-offs upon two choices.

V. Conclusion

In this paper, we propose a LBT algorithm with adaptive CCA threshold to meet the change of various cellular networks traffic load. Simulation results show that the proposed algorithm can greatly enhance the performance of the cellular network at the expense of acceptable sacrifice on WLAN performance, especially in heavy traffic load conditions. The improved LBT algorithm including two types of control functions can either get greater performance gain or impact less on WLAN performance, but neither of them can realize both.

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