This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVT.2019.2940123, IEEE Transactions on Vehicular Technology

An Optimal Channel Occupation Time Adjustment Method for LBE in Unlicensed Spectrum

Qian Wang, Xiaojiang Du, *Senior Member, IEEE,* Zhipeng Gao*, *Member, IEEE,* Mohsen Guizani, *Fellow, IEEE*

***Abstract*—Load Based Equipment (LBE) mechanism is a category of Listen-Before-Talk (LBT) protocol adopted by LTE to access unlicensed channels to realize fair coexistence between LTE and Wi-Fi networks. However, most LBE optimization methods fix Channel Occupation Time (COT) in LBE neglecting its influence on network throughput and fairness. In the paper, considering the influence, we propose an optimal COT adjustment method for the LBE mechanism to maximize the throughput of LTE while satisfying the LTE users' data rate demands and ensuring the fairness coexistence between LTE and Wi-Fi networks. To this end, we first propose a method to separately calculate the throughput of LTE network and Wi-Fi network on the coexistence unlicensed spectrum considering the synchronous of LTE on licensed and unlicensed spectrum, and then utilize a virtual Wi-Fi network construction method to assure the used fairness criterion. Based on the aforementioned methods the problem of throughput maximization of LTE is formulated as a constrained non-linear optimization problem solved by an optimal algorithm. Simulation results prove our proposed throughput calculation method is valid, and then demonstrate the LBE mechanism using our proposed method optimizes the throughput of the SBS network and ensures fairness.**

***Index Terms*—Unlicensed spectrum sharing, LBT, LBE, fairness criterion, throughput maximization.**

I. Introduction

THE penetration of smart devices has led to the existing cellular systems facing the challenge of scarce spectrum resource [1], [2]. To solve the problem, 3rd Generation Partnership Project (3GPP) and some leading companies such as Qualcomm, Huawei, Verizon propose to extend the new-generation of LTE systems to the unlicensed 5GHz spectrum [3], [4]. However, the unlicensed spectrum has been used by Wi-Fi networks, which utilize contention-based Medium Access Control (MAC) through Carrier Sensing Multiple Access (CSMA) and Distributed Coordination Function (DCF) protocols to resolve packet collision. Extending LTE with centralized user admission and MAC protocol to the unlicensed spectrum will largely decrease the performance of Wi-Fi networks [5]–[7]. Therefore, 3GPP proposes Licensed Assisted Access (LAA) technology, in which Listen-Before-Talk (LBT) approach is adopted by each Small Base Station (SBS) to access unlicensed channels to realize fair coexistence between LTE and Wi-Fi networks in the 5GHz unlicensed spectrum.

LBT as a channel accessing mechanism used to realize fair coexistence, it has two categories: Frame Based Equipment (FBE) and Load Based Equipment (LBE) illustrated in Fig. 1. FBE: Frame structure is divided into periods with a fixed length. Before transmitting on a channel the device performs a Clear Channel Assessment (CCA) check based on energy detection lasting at least $20\mu s$ at the end of the fixed period. If the channel is idle during the CCA check period, the device transmits immediately for a duration that equals to Channel Occupancy Time (COT) and then it should have an idle period which is more than 5% of COT; otherwise, the device defers transmission and repeats the CCA check at the end of the next frame. LBE: before every burst of transmission a device shall perform a CCA check where it observes the channel for a defer duration. If the channel is sensed idle and the current transmission is not immediately after a successful transmission, the device starts transmission; otherwise it reverts to the extended CCA (eCCA) which is a back-off procedure (the back-off counter is decremented by 1 every eCCA slot time), and starts to transmit when the back-off counter becomes 0.

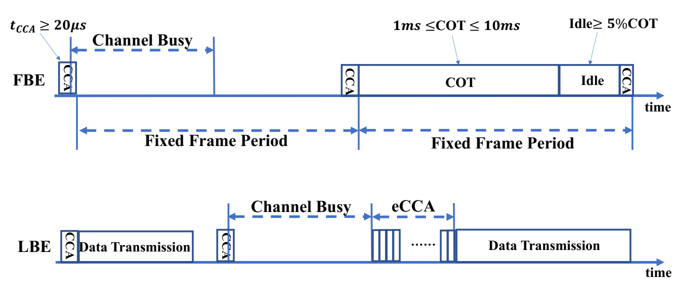


Fig. 1. Two categories of the LBT mechanism.

In 3GPP Rel. 13 [8] LAA is mandated to implement the LBE as a coexistence protocol, and what's more, comparing with FBE which will wait for a long fixed frame period if one CCA check fails, LBE allows for more channel access opportunities because the transmitter can continuously detect the channel [9]. Hence, in the paper we enforce the SBS

Manuscript received December 7, 2018; revised June 25, 2019; accepted August 21, 2019. This work was supported in part by the US Nation Science Foundation (NSF) under grants CNS-1564128 and CNC-1824440. The review of this paper was coordinated by Dr. Linglong Dai. *(Corresponding Author: Zhipeng Gao)*

Q. Wang and Z. Gao are with the State Key Laboratory of Networking and Switching Technology, Beijing University of Posts and Telecommunications, Beijing 100876, China (e-mail: wangqian1991@bupt.edu.cn; gaozhipeng@bupt.edu.cn).

X. Du is with the Department of Computer and Information Science, Temple University, Philadelphia, PA 19122, USA (e-mail: dxj@ieee.org).

M. Guizani is with the Department of Computer Science and Engineering, Qatar University, Qatar (e-mail: mguizani@ieee.org).

using LBE mechanism to access unlicensed spectrum. The final standardized frozen Technical Specification (TS) 36.213 of 3GPP release 13 and 14 fix the COT in LBE mechanism based on priority class number [10], for example, when the LBE priority class number is 1, the allowed COT is $2ms$. However, [11], [12] point out the fixed COT is inefficient under the varying traffic load of the coexistence network. Intuitively, when the throughput of Wi-Fi network becomes small, the efficiency of the spectrum decreases if COT is still set too short. Therefore, how to adjust the COT of SBS in LBE to optimize the efficiency of the unlicensed spectrum is an important issue.

The fairness is an important constraint in the process of adjusting the COT of SBS on unlicensed spectrum. However, there is no standard to reach a consensus. The now existing work evaluates fairness based on their requirements using different standard. For example, [13] evaluates fairness regarding the amount of time of each entity accessing the wireless channel, and [14] uses the throughput to quantify the fairness. Recently, a new fairness criterion based on 3GPP proposed fairness in Rel. 13 [8] is proposed in [15], [16]. The definition is an LTE network does not impact the performance of the Wi-Fi network on a carrier more than an additional Wi-Fi network operating on the same carrier and offering the same level of traffic load of the LTE network. None of the existing LBE optimal methods adopts the criterion to evaluate fairness. In the paper, we use the criterion.

Therefore, in this paper, we focus on adaptively adjusting COT of every SBS user in different unlicensed channels to maximize the throughput of the SBS on the unlicensed spectrum while ensuring fair coexistence between SBS and Wi-Fi networks on every unlicensed channel and satisfying the SBS users' data rate demands. The problem is formulated as a non-linear programming problem, and we use the interior method to solve it. The proposed COT adjustment method is in fact based on centralized scheduling on each SBS. Our major contributions are summarized as follows:

- **Modeling:** to the best of our knowledge, this is the first work using the new proposed criterion to evaluate fairness in the procedure of adjusting COT of SBS in unlicensed channels.
- **Parameter calculation:** we propose a method to separately calculate the throughput of SBS and the Wi-Fi network on a coexistence unlicensed channel. In the calculation, we consider the synchronization of SBS on licensed and unlicensed spectrum. What's more, to satisfy fairness, we use a method proposed in our former paper [17] to construct a virtual Wi-Fi network.
- **Performance evaluation:** we first prove our proposed throughput calculation method for the LTE and Wi-Fi coexistence network is valid, and then simulation results prove the performance of LBE using our proposed COT adjustment method outperforms other two COT adjustment methods from the aspects of LTE users' throughput and fairness assurance.

The remainder of this paper is organized as follows. In Section II, we describe the network model and the problem formulation. In Section III, we present the methods of calculating related parameters in problem formulation. Section IV shows the optimal algorithm, and the performance of the proposed method is evaluated in Section V. We describe related work in Section VI and conclude the paper in Section VII.

II. Network Model and Problem Formulation

We consider coexisting LTE and Wi-Fi networks. The unlicensed spectrum is divided into non-overlapped channels, for example, channels 1, 6, 11 in the 2.4GHz band and channels 36, 40, 44, $\ldots$, 64 in the 5GHz spectrum. We assume different Wi-Fi AP uses different unlicensed channel to avoid strong co-channel interference, and every Wi-Fi network is in the coverage range of other Wi-Fi networks to avoid hidden node problem which is the collision produced by undetected nodes. In the coexistence network, the set of Wi-Fi networks W is in the coverage of a single LTE Small Base Station (SBS) with users $U(|U| = m)$, as shown in Fig. 2, where the circle with solid line represents the coverage range of the SBS; the circle with dotted line represents the coverage range of the Wi-Fi network and lines with arrow represent used unlicensed channels of Wi-Fi networks. Let C represent the set of unlicensed channels accessing by Wi-Fi networks W and the Wi-Fi AP accessing the unlicensed channel $i \in C$ is represented by AP_i, which constructs the network w_i with its served n_i stations.

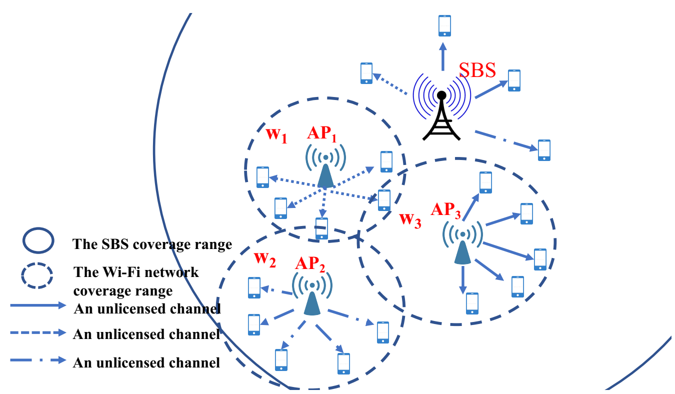


Fig. 2. The network model.

Comparing with the Wi-Fi AP using one channel to serve its stations, the SBS by Carrier Aggregation (CA) technology can aggregate multiple non-contiguous unlicensed channels as complementary channels. $t_{j,i}$ represents the time duration of the SBS user $j \in U$ occupying the channel i and its range is shown in (1). The problem of the paper is to help the SBS adaptively adjust $t_{j,i}(\forall j, \forall i)$ to maximize the throughput of the SBS on unlicensed spectrum while ensuring the fairness between the SBS and Wi-Fi networks on every unlicensed channel and satisfying SBS users' downlink data rate demands. In this paper, we assume the unlicensed spectrum can satisfy SBS users' downlink data rate demands. The problem can be formulated as:

Maximize: $\sum_{i \in C} \sum_{j \in U} TP_{j,i}$

Subject to:

$$t_{j,i} \geq 0, \forall j, \forall i, \tag{1}$$

$$\sum_{j \in U} t_{j,i} \leq T_{cot}, \forall i, \tag{2}$$

$$\sum_{i \in C} TP_{j,i} \geq R_j, \forall j, \tag{3}$$

$$TP^{l}_{w_i} \geq TP^{w_i^{'}}_{w_i}, \forall i, \tag{4}$$

where $TP_{j,i}$ represents the throughput of the SBS user j on the unlicensed channel i. (2) constrains the allowed maximum COT T_{cot} of the unlicensed channel. (3) represents the SBS users' data rate requirements are guaranteed, where R_j is the minimum required downlink data rate of the SBS user j on unlicensed channels for reaching his/her data rate demand. (4) represents the fairness criterion, where $TP^l_{w_i}$ is the throughput of the Wi-Fi network w_i under the influence of the SBS, $TP^{w_i^{'}}_{w_i}$ is the throughput of w_i under the influence of $w_i^{'}$ offering the same traffic of the SBS on the channel i, and the detailed definition is illustrated in Section III-C.

III. Parameters Calculation

In this section, we first derive R_j, then calculate the throughput of the SBS and the Wi-Fi network on the coexistence unlicensed channel, last elaborate on the expression of the fairness criterion.

A. The Derivation of R_j

In LAA, the downlink data rate of user j consists of two parts. The first is on the licensed spectrum, and the second is on the unlicensed spectrum. Therefore, user j needed data rate on unlicensed channels is

$$R_j = r_j - r^L_j, \tag{5}$$

where r_j is the downlink data rate requirement of j, and r^L_j is the maximum downlink data rate of j on the licensed spectrum. In our scenario, there is only one SBS, which uses OFDMA technique to allocate spectrum resources to its users and shares the unlicensed spectrum with Wi-Fi APs in time-division multiple access (TDMA) way, and Wi-Fi APs use different unlicensed channels to transmit data. Therefore, there is no interference among SBS users, among Wi-Fi APs, between the SBS and a Wi-Fi AP. The maximum downlink data rate of j on the licensed spectrum can be expressed as

$$r^L_j = B^L_j log_2(1 + \frac{P^L_{SBS} h^L_j}{B^L_j N_0}), \tag{6}$$

where B^L_j is the downlink bandwidth of the licensed spectrum allocated to j, P^L_{SBS} is the transmission power of the SBS, h^L_j is the channel gain between j and the SBS on the licensed spectrum, and N_0 is the noise power. What's more, the maximum data rate of j on the unlicensed channel can be expressed as

$$r^{UL}_j = B_c log_2(1 + \frac{P^{UL}_{SBS} h^{UL}_j}{B_c N_0}), \tag{7}$$

where B_c is the bandwidth of the unlicensed channel, P^{UL}_{SBS} is the transmission power allocated to the SBS on the unlicensed spectrum, h^{UL}_j is the channel gain between j and the SBS on an unlicensed channel.

B. The Throughput of the SBS and the Wi-Fi Network

In the section, we calculate the throughput of the SBS and the Wi-Fi network on a coexistence unlicensed channel, and we assume all SBSs and Wi-Fi networks are in the saturated condition that means SBSs and Wi-Fi stations will immediately have a packet available for transmission after the completion of each successful transmission.

The SBS: it accesses the unlicensed channel based on the LBE described in the final specification of LTE-LAA TS 36.123 [10]. Before transmitting, the SBS performs CCA using energy detection where it observes the channel for a defer period. The defer period depends on the access priority class number of the transmitted LBE frame. If sensed idle and the current transmission does not immediately follow a successful transmission, the SBS starts transmission; otherwise the SBS performs an eCCA check based on the exponential back-off strategy, i.e., it selects a back-off counter and decreases the back-off counter every slot. The process continues until the counter reaches zero, and then the SBS has a transmission opportunity. When a collision happens in the transmission process, the SBS re-enters the back-off procedure, and the back-off number is selected randomly from a contention window $[0, 2^c W_0 - 1]$ where c is the time of retransmission, and W_0 is the minimum contention window size. When c exceeds the maximum retransmission time m, it stays at the maximum window size for e_l times; then c resets to 0.

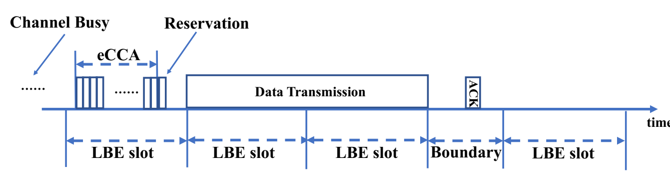


Fig. 3. Synchronous LBE frame

In the process mentioned above, the SBS senses the channel based on the Wi-Fi slot ($t_w = 9\mu s$), but it begins its data transmission based on the LTE slot t_l. To maintain synchronization with the licensed LTE frame, the SBS will reserve the channel until the start of the next LTE slot via sending a reservation signal, when it gets a data transmission opportunity [18] as illustrated in Fig. 3. In the paper, we assume the SBS station is in saturated condition, hence, the SBS always performs the eCCA check since there are always data pending for transmission. The Markov chain of LBE mechanism for the saturated SBS is shown in Fig. 4. Let $\{s(t) = r, b(t) = k\}$ denote the possible states in the Markov chain, where $s(t)$ is the retransmission stage, $b(t)$ is the back-off counter. The one-step transition probabilities are:

$$p\{r, k|r, k+1\} = 1, k \in (0, W_i - 2), r \in (0, m + e_l), \tag{8}$$

$$p\{0, k|r, 0\} = \frac{1 - p^l_i}{W_0}, k \in (0, W_0 - 1), r \in (0, m + e_l), \tag{9}$$

$$p\{r,k|r-1,0\} = \frac{p_i^l}{W_i}, k \in (0, W_i - 1), r \in (0, m+e_l), \quad (10)$$

$$p\{0,k|m+e_l,0\} = \frac{p_i^l}{W_0}, k \in (0, W_m - 1), \quad (11)$$

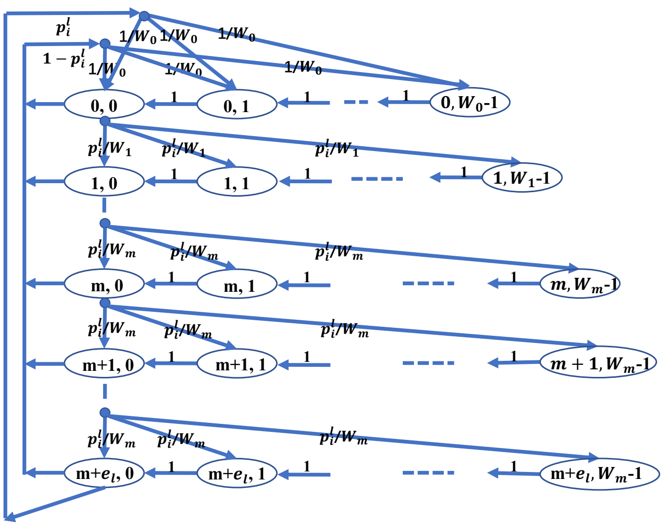


Fig. 4. State transmission diagram

where p_i^l is the probability that a transmitted packet of the SBS encounters a collision in the unlicensed channel i, and $W_i = 2^c W_0$ is the contention window size at the retransmission stage c. (8) is the transition probability of the back-off counter from $(k+1)$ to k; (9) represents the transition probability after successful transmission; (10) is the transition probability after unsuccessful transmission; (11) is the transition probability after unsuccessful transmission in $(m+e_l)$th retransmission stage. In the steady state, we derive (12) from [19], where $b_{r,k}(k \in (0, W_i - 1), r \in (0, m+e_l))$ is the stationary distribution of the Markov chain; τ_i^l is the probability that the SBS transmits during a genetic slot time in the unlicensed channel i.

$$\begin{aligned}\tau_i^l &= \sum_{r=0}^{m+e_l} b_{r,0} \\ &= \frac{2}{W_0\left(\frac{(1-p_i^l)(1-(2p_i^l)^{m+1})}{(1-2p_i^l)(1-(p_i^l)^{m+e_l})} + 2^m \frac{(p_i^l)^{m+1}-(p_i^l)^{m+e_l+1}}{1-(p_i^l)^{m+e_l+1}}\right) + 1}.\end{aligned} \quad (12)$$

The Wi-Fi network: Wi-Fi stations access the unlicensed channel based on 802.11 by the Distributed Coordination Function (DCF) – a distributed slotted medium access scheme based on Carrier Sensing Multiple Access Collision Avoidance (CSMA/CA) protocol and the corresponding request-to-send/clear-to-send (RTS/CTS) access mechanisms. Based on the Bianchi model [20], the probability τ_i^w that a Wi-Fi station in w_i occupies the channel i to transmit in a randomly chosen slot time is expressed in (13).

$$\tau_i^w = \frac{2}{1 + cw_i^w + p_i^w cw_i^w \sum_{k=0}^{m_i} (2p_i^w)^k}, \quad (13)$$

where cw_i^w is the minimum size of contention window of w_i, m_i is the maximum retransmission stage of w_i, and p_i^w is the probability that a transmitted packet of a station in w_i encounters a collision.

The probability τ_i^l that SBS transmits data during a slot in the channel i is calculated using (12). The SBS shares the unlicensed channel i with the Wi-Fi network w_i composed of n_i stations. In the scenario, in a random slot the collision probability of the SBS with at least one of Wi-Fi stations is calculated by (14), and the collision probability of a Wi-Fi station with at least one of other remaining Wi-Fi stations or the SBS is calculated using (15).

$$p_i^l = 1 - (1 - \tau_i^w)^{n_i}, \quad (14)$$

$$p_i^w = 1 - (1 - \tau_i^l)(1 - \tau_i^w)^{n_i - 1}. \quad (15)$$

$p_i^l, p_i^w, \tau_i^l, \tau_i^w$ can be calculated by jointly integrating (12)-(15), since other used parameters such as m, e_l, W_0, cw_i^w are known. To compute the average throughput of SBS or the Wi-Fi network on a channel, the average time duration of a transmission is needed. It should contain events of successful transmission of the SBS, successful transmission of the Wi-Fi station, the confliction among Wi-Fi stations and the confliction between the SBS and the Wi-Fi station. The average time duration in channel i is:

$$t_{ai} = p_{ii} t_w + p_{si}^w t_{si}^w + p_{si}^l t_{si}^l + p_{ci}^w t_{ci}^w + p_{ci}^l t_{ci} \quad (16)$$

where

$$\begin{aligned}
p_{ii} &= (1-\tau_i^l)(1-\tau_i^w)^{n_i}, \\
p_{si}^w &= n_i \tau_i^w (1-\tau_i^w)^{n_i-1}(1-\tau_i^l), \\
t_{si}^w &= RTS/C + CTS/C + (H + E_{w_i}[p])/C + \\
&ACK/C + 3SIFS + DIFS + 4\sigma, \\
p_{si}^l &= \tau_i^l (1-\tau_i^w)^{n_i}, \\
t_{si}^l &= t_{ri}^l + \sum_{j \in U} t_{j,i} + t_b, \\
t_{ri}^l &= \frac{1}{\left\lfloor \frac{t_l}{t_w} \right\rfloor} \sum_{k=0}^{\lfloor \frac{t_l}{t_w} \rfloor - 1} k t_w, \\
p_{ci}^w &= (1 - (1-\tau_i^w)^{n_i} - n_i \tau_i^w (1-\tau_i^w)^{n_i-1})(1-\tau_i^l), \\
t_{ci}^w &= RTS/C + DIFS + \sigma, \\
p_{ci}^l &= \tau_i^l (1 - (1-\tau_i^w)^{n_i}).
\end{aligned}$$

p_{ii} is the probability that i is idle in a slot. t_w is the duration of the Wi-Fi slot because the SBS and Wi-Fi stations compete a channel based on the Wi-Fi slot. p_{si}^w is the probability of a successful transmission of a station of w_i on i, and t_{si}^w is the time duration of the transmission, where $E_{w_i}[p]$ is the transmitted packet size of a Wi-Fi station, H is the packet header, C is the channel data rate, σ is the propagation delay, and $RTS, CTS, ACK, SIFS, DIFS$ are parameters in the RTS/CTS mechanism of the Wi-Fi network.

p_{si}^l is the probability of a successful transmission of the SBS on i, and t_{si}^l is the time duration of the transmission that contains the channel reservation time t_{ri}^l after getting the transmission opportunity and the data transmission time of SBS users on i and a boundary slot t_b followed by the data transmission. t_{ri}^l is the average value of all possible reservation time. p_{ci}^w is the probability that the channel is conflicted by Wi-Fi stations, and t_{ci}^w is the duration of the confliction. p_{ci}^l is the probability that the SBS and a Wi-Fi station conflict the channel, t_{ci} represents the conflict duration determined by the larger value between t_{ci}^l and t_{ci}^w. t_{ci}^l is the time duration of a failure data transmission of the SBS, which is the same with the time of the successful data transmission t_{si}^l because the SBS gets the failure message until the end of the data transmission. t_{ci}^w is the time duration of a failure data transmission of a Wi-Fi station. Based on 802.11 standards, RTS is $304bits$ and DIFS equals to $34\mu s$. The maximum value of t_{ci}^w is approximately equal to $186\mu s$ when the data rate of the Wi-Fi network is minimum $(2Mbps)$ and $\sigma = 0.1\mu s$. The value is much smaller than t_{ci}^l with a constraint of at least $1ms$. Thus, in the paper $t_{ci} = t_{ci}^l = t_{si}^l$. We use a function with variable $t_{j,i}$ to express t_{ai} where b_{i1}, b_{i2}, b_{i3} are constants shown as follows:

$$t_{ai} = b_{i1} + b_{i2}(b_{i3} + \sum_{j \in U} t_{j,i}) \tag{17}$$

where

$$\begin{aligned} b_{i1} &= p_{ii}t_w + p_{si}^w t_{si}^w + p_{ci}^w t_{ci}^w, \\ b_{i2} &= p_{si}^l + p_{ci}^l, \\ b_{i3} &= t_{ri}^l + t_b. \end{aligned}$$

The methods of calculating the throughput $TP_{j,i}$ of the SBS user j on i, the throughput TP_i^l of SBS on i and the throughput $TP_{w_i}^l$ of w_i under the influence of the SBS are respectively illustrated as follows:

$$\begin{aligned} TP_{j,i} &= \frac{p_{si}^l r_j^{UL} t_{j,i}}{t_{ai}}, \\ TP_i^l &= \sum_{j \in U} TP_{j,i}, \\ TP_i^w &= \frac{p_{si}^w E_{w_i}[p]}{t_{ai}}. \end{aligned}$$

C. The Fairness Criterion

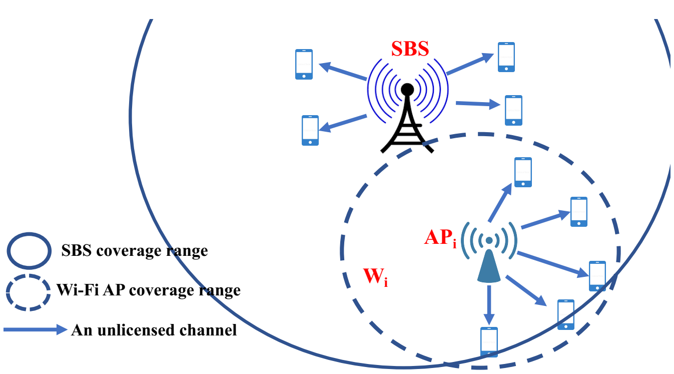


Fig. 5. The w_i shares the unlicensed channel i with SBS.

Some SBS users are assigned to share the unlicensed channel i with Wi-Fi network w_i, as shown in Fig. 5, where the line with arrow represents the used unlicensed channel i; the circle with solid line represents the coverage range of SBS; the circle with dotted line represents the coverage range of w_i. In the paper, the adopted fairness criterion is the LTE network does not impact the throughput of the Wi-Fi network on a carrier more than an additional Wi-Fi network operating on the same carrier and offering the same level of traffic load of the LTE network. Therefore, the fairness criterion on the coexistence channel i is the throughput $TP_{w_i}^l$ of w_i under the influence of the SBS should be larger than the throughput $TP_{w_i}^{w_i'}$ of w_i under the influence of another network w_i', which offering the same traffic load of the SBS and occupying the same channel of w_i illustrated in Fig. 6, where the circle with dotted line represents the coverage range of the Wi-Fi network, and the line with arrow represents the two networks use the same unlicensed channel.

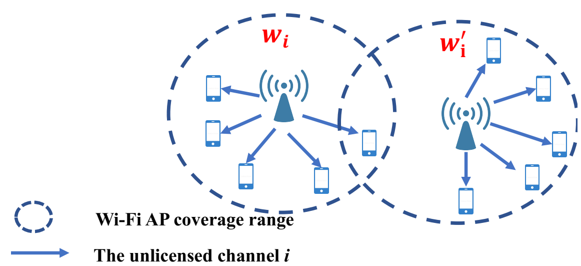


Fig. 6. The w_i shares the unlicensed channel i with w_i'.

Considering the scenario that on the channel i the Wi-Fi network offering the same traffic of SBS may not exist, a virtual network w_i' with n_i' users is constructed. We set the size of its contention window $cw_i^{w'}$ and its maximum retransmission times m_i' are same with w_i. Bianchi model [24] proposed a method to calculate the throughput of w_i', when w_i' occupies a channel alone, illustrated as follows:

$$TP_{w_i'} = \frac{p_{tri}^{w'} p_{si}^{w'} E_{w_i'}[p]}{(1-p_{tri}^{w'})t_w + p_{tri}^{w'} p_{si}^{w'} t_{si}^{w'} + p_{tri}^{w'}(1-p_{si}^{w'}) t_{ci}^{w'}} \tag{18}$$

where

$$\begin{aligned} t_{si}^{w'} &= RTS/C + CTS/C + (H + E_{w_i'}[p])/C + \\ & ACK/C + 3SIFS + DIFS + 4\sigma, \\ t_{ci}^{w'} &= RTS/C + DIFS + \sigma, \\ \tau_i^{w'} &= \frac{2}{1 + cw_i^w + p_i^{w'} cw_i^w \sum_{k=0}^{m_i} (2p_i^{w'})^k}, \\ p_i^{w'} &= 1 - (1 - \tau_i^{w'})^{n_i'-1}, \\ p_{tri}^{w'} &= 1 - (1 - \tau_i^{w'})^{n_i'}, \\ p_{si}^{w'} &= \frac{n_i' \tau_i^{w'} (1 - \tau_i^{w'})^{n_i'-1}}{p_{tri}^{w'}}. \end{aligned}$$

$\tau_i^{w'}$ is the probability that a Wi-Fi station in w_i' transmits in a slot time, where $p_i^{w'}$ represents the probability that a transmitted packet of a station in w_i' encounters a collision; $p_{tri}^{w'}, p_{si}^{w'}$ respectively represent the probability that there is

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVT.2019.2940123, IEEE Transactions on Vehicular Technology

at least one transmission in a slot time and the successful transmission on channel i; t_w is the duration of an empty slot time; $t_{ci}^{w'}$ is the average time that the channel is sensed busy by each station during a collision; $t_{si}^{w'}$ is the average time that the channel is sensed busy because of a successful transmission; $E_{w_i'}[p]$ is the average size of the delivery packet in w_i'. According to (18) the specific throughput of a Wi-Fi network can also be got by changing the size of the delivery packet besides changing the number of stations, and the feasibility has been proved in Section V-C. Therefore, to achieve the throughput of the SBS on the channel i (TP_i^l) the average delivery packet size of w_i' with n_i' stations is:

$$E_{w_i'}[p] = \frac{\{\frac{((1-p_{tri}^{w'})t_w + p_{tri}^{w'}(1-p_{si}^{w'})t_{ci}^{w'})C}{p_{tri}^{w'}p_{si}^{w'}} + YC\}TP_i^l}{C - TP_i^l} \quad (19)$$

where

$$Y = RTS/C + CTS/C + H/C + ACK/C + 3SIFS + DIFS + 4\sigma.$$

When w_i' occupies the same channel of w_i, the throughput of the hybrid network is similar to a Wi-Fi network with $(n_i + n_i')$ stations occupied the channel alone. The throughput of the hybrid network is:

$$TP_{w_i+w_i'} = \frac{p_{tri}^{hw}p_{si}^{hw}E_{hw}[p]}{(1-p_{tri}^{hw})t_w + p_{tri}^{hw}p_{si}^{hw}t_{si}^{hw} + p_{tri}^{hw}(1-p_{si}^{hw})t_{ci}^{hw}} \quad (20)$$

where

$$E_{hw}[p] = \frac{n_iE_{w_i}[p] + n_i'E_{w_i'}[p]}{n_i + n_i'},$$
$$\tau_i^{hw} = \frac{2}{1 + cw_i^w + p_i^{hw}cw_i^w\sum_{k=0}^{m_i}(2p_i^{hw})^k},$$
$$p_i^{hw} = 1 - (1-\tau_i^{hw})^{n_i+n_i'-1},$$
$$p_{tri}^{hw} = 1 - (1-\tau_i^{hw})^{n+n_i'},$$
$$p_{si}^{hw} = \frac{n_i + n_i'\tau_i^{hw}(1-\tau_i^{hw})^{n_i+n_i'-1}}{p_{tri}^{hw}},$$
$$t_{si}^{hw} = RTS/C + CTS/C + (H + E_{hw}[p])/C + ACK/C + 3SIFS + DIFS + 4\sigma,$$
$$t_{ci}^{hw} = RTS/C + DIFS + \sigma.$$

Therefore, the throughput $TP_{w_i}^{w_i'}$ of the Wi-Fi AP w_i under the influence of w_i' is transformed to (21) by integrating (19), (20), in which $\alpha_{i1}, \alpha_{i2}, \alpha_{i3}, \alpha_{i4}$ are constants, since the some parameters used to calculate them are known such as $C, n_i, n_i', E_{w_i}[p], t_w, Y, t_{ci}^{hw}$, and other parameters can be calculated based on above-listed equations such as $p_{tri}^{w'}, p_{si}^{w'}, p_{tri}^{hw}, p_{si}^{hw}$.

$$TP_{w_i}^{w_i'} = \frac{n_iE_{w_i}[p]}{n_iE_{w_i}[p] + n_i'E_{w_i'}[p]}TP_{w_i+w_i'} = \frac{\alpha_{i1} + \alpha_{i2}TP_i^l}{\alpha_{i3} + \alpha_{i4}TP_i^l} \quad (21)$$

where

$$\alpha_{i1} = Cn_ip_{tri}^{hw}p_{si}^{hw}p_{tri}^{w'}p_{si}^{w'}E_{w_i}[p],$$
$$\alpha_{i2} = -n_ip_{tri}^{hw}p_{si}^{hw}p_{tri}^{w'}p_{si}^{w'}E_{w_i}[p],$$
$$\alpha_{i3} = Cp_{tri}^{w'}p_{si}^{w'}(n_i + n_i')((1-p_{tri}^{hw})t_w + p_{tri}^{hw}(1-p_{si}^{hw})* t_{ci}^{hw} + p_{tri}^{hw}p_{si}^{hw}Y) + Cn_ip_{tri}^{hw}p_{si}^{hw}p_{tri}^{w'}p_{si}^{w'}E_{w_i}[p],$$
$$\alpha_{i4} = Cn_i'p_{tri}^{hw}p_{si}^{hw}((1-p_{tri}^{w'})t_w + Cp_{tri}^{w'}(1-p_{si}^{w'})t_{ci}^{w} + Cp_{tri}^{w'}p_{si}^{w'}Y) - p_{tri}^{w'}p_{si}^{w'}\{(n_i + n_i')((1-p_{tri}^{hw})t_w + p_{tri}^{hw}(1-p_{si}^{hw})t_{ci}^{hw} + p_{tri}^{hw}p_{si}^{hw}Y) + n_ip_{tri}^{hw}p_{si}^{hw}E_{w_i}[p]\}.$$

IV. THE OPTIMAL ALGORITHM

According to the calculation of parameters, the problem formulation can be concretely written as:

Maximize: $\sum_{i\in C}\sum_{j\in U}\frac{p_{si}^l r_j^{UL}t_{j,i}}{b_{i1} + b_{i2}(b_{i3} + \sum_{j\in U}t_{j,i})}$

Subject to:

$$t_{j,i} \geq 0, \forall j, \forall i,$$
$$\sum_{j\in U}t_{j,i} \leq T_{cot}, \forall i,$$
$$\sum_{i\in C}\frac{p_{si}^l r_j^{UL}t_{j,i}}{b_{i1} + b_{i2}(b_{i3} + \sum_{j\in U}t_{j,i})} \geq R_j, \forall j,$$
$$\frac{p_{si}^wE_{w_i}[p]}{b_{i1} + b_{i2}(b_{i3} + \sum_{j\in U}t_{j,i})} \geq \frac{\alpha_{i1}(b_{i1} + b_{i2}(b_{i3} + \sum_{j\in U}t_{j,i})) + \alpha_{i2}\sum_{j\in U}p_{si}^l r_j^{UL}t_{j,i}}{\alpha_{i3}(b_{i1} + b_{i2}(b_{i3} + \sum_{j\in U}t_{j,i})) + \alpha_{i4}\sum_{j\in U}p_{si}^l r_j^{UL}t_{j,i}}, \forall i,$$

where all parameters such as $p_{si}^l, r_j^{UL}, p_{si}^w$ are constants except that $t_{j,i}$ is variable. The formulated problem is a non-linear programming problem. In this paper, we directly use the interior point method to solve the problem. The method proposes to construct a barrier function (22) to transform the problem into an optimization problem with no constraint.

$$f(t) = -\sum_{i\in C}\sum_{j\in U}\frac{p_{si}^l r_j^{UL}t_{j,i}}{b_{i1} + b_{i2}(b_{i3} + \sum_{j\in U}t_{j,i})} + \mu* (\sum_{i\in C}\sum_{j\in U}log t_{j,i} + \sum_{j\in U}log g_i(t) + \sum_{i\in C}log(-k_i(t) - l_i(t))) \quad (22)$$

where

$$g_i(t) = \sum_{i\in C}\frac{p_{si}^l r_j^{UL}t_{j,i}}{b_{i1} + b_{i2}(b_{i3} + \sum_{j\in U}t_{j,i})} - R_j,$$
$$k_i(t) = \sum_{j\in U}t_{j,i} - T_{cot},$$
$$l_i(t) = p_{si}^wE_{w_i}[p]\{\alpha_{i3}(b_{i1} + b_{i2}(b_{i3} + \sum_{j\in U}t_{j,i})) + \alpha_{i4}\sum_{j\in U}p_{si}^l r_j^{UL}t_{j,i}\} - (b_{i1} + b_{i2}(b_{i3} + \sum_{j\in U}t_{j,i}))* \{\alpha_{i3}(b_{i1} + b_{i2}(b_{i3} + \sum_{j\in U}t_{j,i})) + \alpha_{i4}\sum_{j\in U}p_{si}^l r_j^{UL}t_{j,i}\}.$$

μ is a predetermined constant. Since the linear function, quadratic and log functions are all convex, the constructed barrier function (22) is convex either and the local minimum value is the minimized value. Therefore, the value of t^*, which is the solution that the gradient of the objective function equals to zero showed in (23) ($j \in U, i \in C$), is minimum.

$$\triangledown f(t) = (\triangledown f(t_{j,i})) = 0 \tag{23}$$

where

$$\triangledown f(t_{j,i}) = \frac{\partial f}{\partial t_{j,i}}.$$

The Newton iteration method illustrated in the (24) can be used to effectively solve the transformed problem (22), where H is the derivative of $\triangledown f(t)$. In the iteration, the parameter μ is constant, and the stop condition is $\triangledown f(t^*)$ is smaller than a predefined error value ε. The detailed process is illustrated in **Algorithm** 1. In this paper, considering the integer constraint of COT of SBS, the value of t^* is rounded down.

$$t_{n+1} = t_n - H^{-1} \triangledown f(t) \tag{24}$$

where

$$H = \left[\forall i, \forall j \frac{\partial \triangledown f}{\partial t_{j,i}} \right].$$

Algorithm 1 The interior algorithm

Input: the objective function, constraints, $\mu, \varepsilon, t_{(0)}$
Output: t^*

```
t* = t_(0); //the initial value
n = 1;
while (∇f(t*) ≥ ε) do
    t_{n+1} = t_n − H^{-1} ∇ f(t);
    t* = t_{n+1};
    n = n + 1;
end while
return t*;
```

TABLE I
THE WI-FI NETWORK PARAMETERS

Wi-Fi network	The number of stations	Data Packet Size/Bytes	A data item transmission duration/ms	Throughput /Mbps
1	5	1500	0.22222	30.853
2	10	1200	0.17778	27.699
3	15	1000	0.14815	25.016

TABLE II
NS3 SIMULATION PARAMETERS

parameters	values	comments
CW^w_{min}	15	The minimum size of Wi-Fi contention window
CW^w_{max}	1023	The maximum size of Wi-Fi contention window
m	6	The maximum back-off times of Wi-Fi CW
ACK	364bits	The size of ACK frame
CTS	352bits	The size of CTS frame
RTS	304bits	The size of RTS frame
SIFS	$16\mu s$	Short interframe space
DIFS	$34\mu s$	Distributed interframe space
H	416bits	The header size of transferred Wi-Fi packets
σ	0	The propagation delay
T_w	$9\mu s$	The Wi-Fi slot time
T_l	1ms	The LTE slot time
T_b	0.5ms	The LTE boundary slot time
CW^l_{min}	15	The minimum size of LTE contention window
CW^l_{max}	1023	The maximum size of LTE contention window
e_l	5	The time of staying the maximum CW
T_{cot}	8ms	The COT of LTE

V. THE PERFORMANCE EVALUATION

In this section, we evaluate our proposed method from three aspects. The first is to demonstrate the influence of the COT of LTE on the throughput and fairness of the network. Then, we prove our proposed throughput calculation method for the LTE and Wi-Fi coexistence network and the used Wi-Fi network construction method is valid. At last we evaluate the performance of our proposed method from aspects of LTE users' throughput and fairness.

A. The Influence of the COT of LTE

To demonstrate the influence of the COT of LTE on the throughput and fairness of the network, we construct the Wi-Fi and LTE coexistence network based on the LTE/Wi-Fi coexistence model [21] in an event-driven network simulator (NS3). The constructed network has one SBS, and three Wi-Fi networks. In the Wi-Fi network, Wi-Fi stations transmit uplink traffic to the AP based on IEEE 802.11n protocol operating at an unlicensed channel with RTS/CTS mechanism, whereas the LTE SBS accesses the same channel scheduling downlink transmissions to its associated user based on the synchronized LBE and it can access multiple unlicensed channels by carrier aggregation. The data rate of the channel is 54Mbps. Every Wi-Fi station generates a packet at an interval of 200 microseconds to make sure that saturation conditions exist at 54Mbps data rate and below.

The parameters of Wi-Fi networks are illustrated in TABLE I, and other NS3 simulation parameters are listed in TABLE II. First, we evaluate the throughput of SBS, the Wi-Fi network and the total throughput of SBS and Wi-Fi on an unlicensed channel with the change of COT of SBS. As shown in Fig. 7 a-c, the throughput of SBS increases with the increase of its COT and at the same time the throughput of the Wi-Fi network occupied the same channel decreases, since the increase of the occupation time of a network will lead to the decrease of another network when the total time is fixed. The total throughput of the channel increases, because the increased throughput of LTE is larger than the reduced throughput of the Wi-Fi network.

Then, we evaluate whether fairness is satisfied with the change of the COT of SBS. The measured fairness criterion is the throughput of a Wi-Fi network w_i under the influence of SBS ($TP^l_{w_i}$) is larger than the throughput of the Wi-Fi network under the influence of the constructed virtual Wi-Fi network $w_i^{'}$ with 5 stations offering the same traffic of the SBS ($TP^{w_i^{'}}_{w_i}$), and it can be expressed by $TP^l_{w_i} > TP^{w_i^{'}}_{w_i} (i \in \{1, 2, 3\})$.

In Fig. 7 d, the solid line represents $TP^l_{w_i}$, and the dotted line with same marker represents $TP^{w_i^{'}}_{w_i}$. The solid line shows that with the increase of the COT of SBS, the throughput

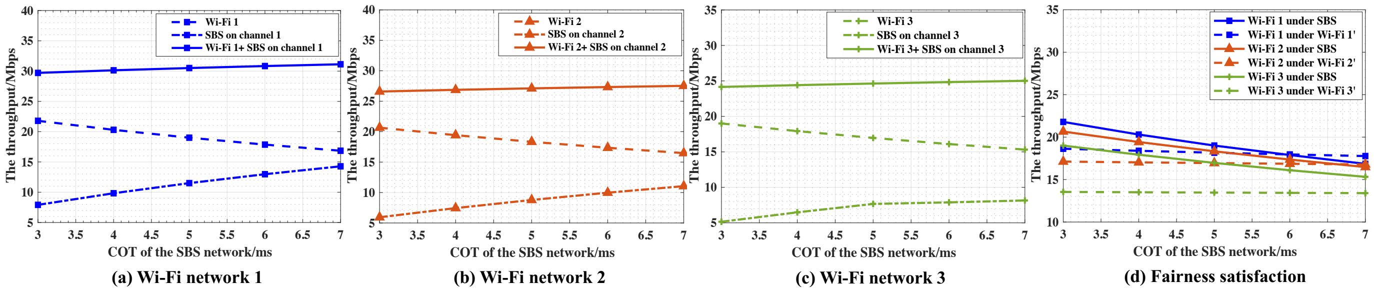


Fig. 7. The throughput of networks with the change of COT.

$TP^{l}_{w_i}$ decreases. The dotted line show the throughput $TP^{w_i'}_{w_i}$ also reduces with the increase of the COT of SBS since the transmitted packet size of the constructed Wi-Fi network w_i' increases to satisfy the increased SBS throughput. However, the reduced value of $TP^{w_i'}_{w_i}$ is small comparing with the reduced value of $TP^{l}_{w_i}$. Therefore, as the increase of the COT of SBS, the fairness criterion will not be satisfied gradually. As shown in Fig. 7 d, the fairness of Wi-Fi network 1 is not satisfied when COT of SBS increases to 7ms. Although the fairness is satisfied for Wi-Fi network 2 and 3, the gap between $TP^{l}_{w_i}$ and $TP^{w_i'}_{w_i}$ continuously decreases with the increase of COT of SBS. In conclusion, the COT of LTE will influence the throughput and the fairness of networks.

B. The Coexistence Network Throughput Calculation Method

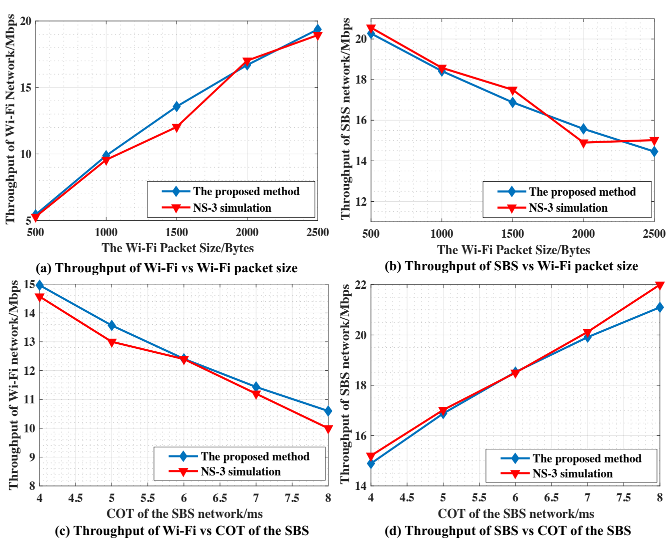


Fig. 8. Comparing the proposed throughput calculation method with NS3 simulation.

To prove the validity of our proposed throughput calculation method, we set up a single hop Wi-Fi network with one AP and 5 Wi-Fi stations, co-existed with an SBS with one user using NS3. Wi-Fi stations transmit uplink traffic to the AP by the unlicensed channel 36 (5.180 GHz), and SBS uses the same channel to download data to its user. The data rate of the channel is 54Mbps. Every Wi-Fi station generates a packet at an interval of 200 microseconds to make sure

TABLE III
TESTIFY THE USED WI-FI NETWORK CONSTRUCTION METHOD

Throughput/Mbps	10	12	14	16	18
Packet size/Bytes	256	322	395	475	564
Throughput/Mbps	10.648	12.933	14.218	15.551	16.998

the saturation condition. Other simulation parameters are set based on TABLE II.

We first compare the Wi-Fi and SBS throughput of our proposed method with simulation results with the change of the Wi-Fi packet size. The COT of SBS is set to 5ms. In the proposed method, all parameters are set based on NS3 simulation parameters. As illustrated in Fig. 8 a and b, the calculated throughputs of the Wi-Fi network and SBS network throughput are similar to the NS3 simulation results.

Then, we compare the Wi-Fi and SBS throughput of the proposed method with simulation results with the change of the COT of SBS. The transmission packet size of the Wi-Fi network is set to 1500 bytes. As illustrated in Fig. 8 c and d, the calculated throughput of the Wi-Fi and SBS network are similar to the NS3 simulation results. Therefore, our proposed coexistence network throughput calculation method is accurate enough to calculate the throughput of the coexistence network.

C. The Wi-Fi Network Construction Method

The Wi-Fi network construction method aims to get the size of the delivery package of a Wi-Fi network to achieve the specific throughput. It is based on our former paper [17]. To testify the feasibility of the method in the paper, we compare the throughput of a Wi-Fi network in NS3, whose packet size is got through our used method, with the specified throughput.

In the NS3 simulation environment, we set the Wi-Fi network with one AP and five stations. Every Wi-Fi station generates a packet with an interval of 200 microseconds, and the data rate of the channel is 54Mbps. Other parameters are same with TABLE II. The simulation results are illustrated in TABLE III.

In TABLE III, the first line is the specific throughput. The second line is the calculated delivery packet size by the used Wi-Fi construction method to reach the throughput of the first line, and the third line is the throughput of the Wi-Fi network using the calculated packet size in NS3 simulation. The results show the throughput of the Wi-Fi network in NS3 is similar

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVT.2019.2940123, IEEE Transactions on Vehicular Technology

TABLE IV
THE SBS USERS

The number of SBS users	The contained SBS users
1	u_1
2	u_1, u_2
3	u_1, u_2, u_3
4	u_1, u_2, u_3, u_4
5	u_1, u_2, u_3, u_4, u_5

TABLE V
THE PARAMETERS OF SBS USERS

The SBS user	The demands of COT/ms	The data rate/Mbps
u_1	2.5000	54
u_2	2.0000	54
u_3	4.4000	54
u_4	1.5000	54
u_5	5.0000	54

to the specific throughput. It proves the specific throughput can be achieved by our used Wi-Fi construction method.

D. The Performance of the Proposed Method

In this section, we compare the performance (throughput) of LBE mechanism using our proposed COT adjustment method with other two mechanisms: the LBE mechanism based on continuous COT and the standard LBT mechanism in TS 36.213 [10] in two simulation scenarios. All parameters such as CW^w_{min}, CW^w_{max} are the same in these three channel access mechanisms except for the COT. The first scenario is changing the number of SBS users, and the second scenario is changing the number of Wi-Fi networks.

LBE with Continuous COT (CCOT): The SBS network accesses the channel using LBE, and continuously occupies unlicensed channels to only satisfy its needed COT without considering the fairness. However, the COT of SBS should not exceed the allowed maximum COT. The method serves as the lower bound. In 3GPP Release 13 [8], when the counter reaches zero, the transmitter can occupy the channel for a maximum amount of time of $q*(13/23)ms$, where q is defined by the manufacturer in the range of $[4, 32]$. Therefore, in the paper, we set the maximum COT is $13ms$.

The standard LBT: the COT of the mechanism is based on the priority class of the transmitted data, for example, the data transmission time is $2ms$ when the priority class number of the data equals to 1; and the transmission time is $8/10ms$ for the data with priority class 4. In our simulation, we set the priority number of transmitted data is 4, and the corresponding transmission time of the data is $10ms$.

The first simulation environment: It has one SBS, and three Wi-Fi networks. As the number of Wi-Fi networks is small, the Wi-Fi networks can use different unlicensed channels. Wi-Fi network 1, 2, 3 occupied unlicensed channels are channel 1, 2, 3, respectively. The SBS accesses these three channels. The data rates of Wi-Fi networks are $54Mbps$, and other parameters of the Wi-Fi networks are same with TABLE I. We evaluate the performance of methods with the change of the number of SBS users. The contained SBS users and related parameters are illustrated in TABLE IV and V.

First, since our proposed method aims to maximize the throughput of the SBS network with the constraint of fairness criterion, and COT of the SBS of accessing the unlicensed channel is fixed in the standard LBT method ($10ms$), these two methods don't consider the number of SBS users in the process of accessing the unlicensed channel. Hence, the throughput of SBS, Wi-Fi networks, the total throughput of SBS and Wi-Fi networks, and the reduced throughput of Wi-Fi networks will not be changed with the increase of SBS users in these two methods as illustrated in Fig. 9.

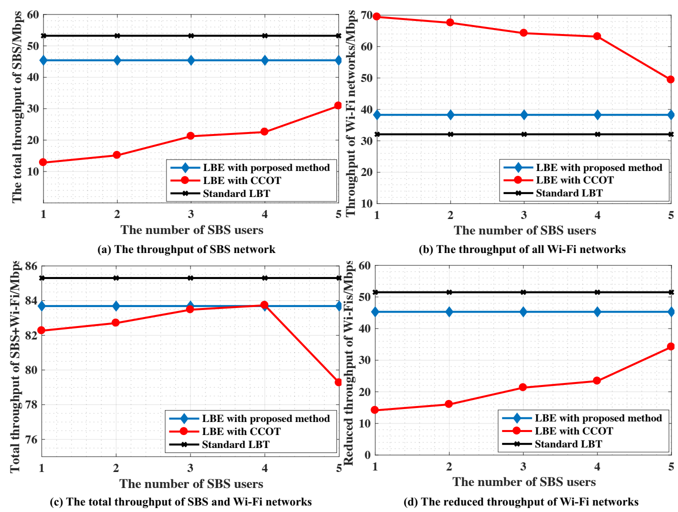
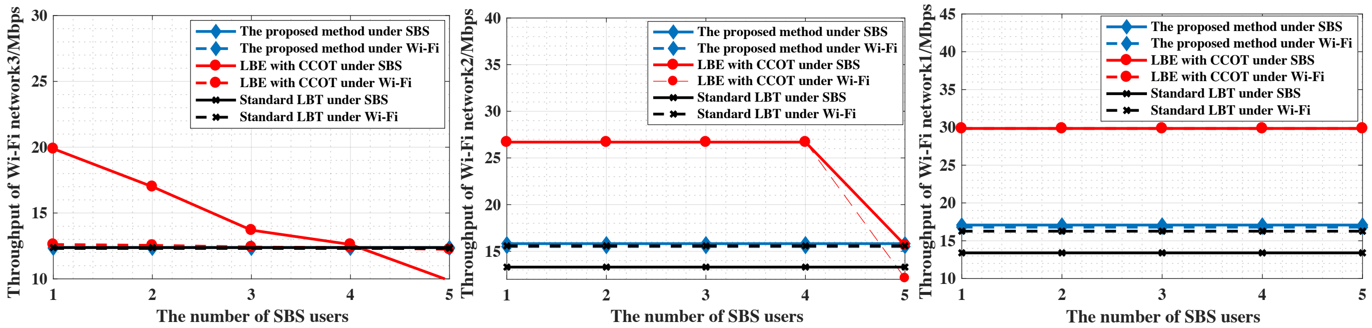


Fig. 9. The throughput of networks in the first simulation environment.

In comparison to the standard LBT method, the throughput of SBS using LBE with our proposed method is smaller shown in Fig. 9 a, since our proposed method considers the fairness in the process of adjusting the COT of SBS. It directly leads to larger throughput of all Wi-Fi networks shown in Fig. 9 b and smaller reduced throughput of all Wi-Fi networks of than the standard LBT method shown in Fig. 9 d. What's more, the influence of varied COT of SBS on the throughput of SBS is larger than its influence on the throughput of Wi-Fi networks. Hence, the total throughput of SBS and Wi-Fi networks of our proposed method is smaller than the standard LBT shown in Fig. 9 c.

The COT of our proposed method is the maximized value satisfying the fairness constraint. The values are $10ms, 5ms, 6ms$ on channels 3, 2, 1 respectively. For the standard LBT method, since its COT is set to $10ms$, the fairness is only satisfied on channel 3, and the throughput of Wi-Fi 3 is the same with our proposed method illustrated in Fig. 10 a. The solid line represents the throughput of Wi-Fi network w_3 under the influence of SBS ($TP^l_{w_3}$), and the dotted line with the same marker represents the throughput of Wi-Fi network w_3 under the influence of $w_3^{'}$ offering the same traffic of SBS accessing the channel 3 ($TP^{w_3^{'}}_{w_3}$). In Wi-Fi network 2 and 1, since the COT of SBS in the standard LBT method is larger than our proposed method, the fairness criterion is not satisfied and the throughputs of the Wi-Fi networks are smaller than our proposed method shown in Fig. 10 b, c.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVT.2019.2940123, IEEE Transactions on Vehicular Technology



(a) The fairness of Wi-Fi network 3 (b) The fairness of Wi-Fi network 2 (c) The fairness of Wi-Fi network 1

Fig. 10. The fairness of Wi-Fi networks in the first simulation environment.

TABLE VI
THE CONTAINED WI-FI NETWORKS

The number of Wi-Fi networks	The contained Wi-Fi networks
3	Wi-Fi network 1, 2, 3
4	Wi-Fi network 1, 2, 3, 4
5	Wi-Fi network 1, 2, 3,4,5
6	Wi-Fi network 1, 2, 3, 4, 5, 6
7	Wi-Fi network 1, 2, 3, 4, 5, 6, 7

Second, since the LBE with CCOT method aims to satisfy COT demands of SBS users, the throughput of SBS and the total throughput of SBS and Wi-Fi are smaller than the LBE with our proposed method and the standard LBT method, and the throughput of the network will be changed with the increase of SBS users. According to the access mechanism the SBS first chooses to occupy the channel of Wi-Fi network whose throughput is minimum. In this scenario, it first occupies channel 3. If the allowed maximum COT of channel 3 still can not satisfy the SBS users demands, then the SBS occupies channel 2, at last occupies channel 1. When the number of SBS users is smaller than 5, COT demands can be satisfied by occupying channel 3. Therefore, the throughputs of Wi-Fi network 2 and 1 do not change with the increase of SBS users shown in Fig. 10 b, c. The SBS needed COT is $8ms$ to satisfy the COT demands of 4 users, it is smaller than fairness constraint 10ms on channel 3. When the number of SBS user is up to 5, its data rate demands can be satisfied by occupying channels 3 and 2. The assigned COTs are $13ms$ on channel 3 and $3ms$ on channel 2. Therefore, for the LBE with CCOT method, the fairness cannot be satisfied on Wi-Fi network 3 shown in Fig. 10 a and can be satisfied on Wi-Fi network 2 and 1 shown in Fig. 10 b, c.

The second simulation environment: it has one SBS and five SBS users. The SBS users' COT demands and their maximum data rates on unlicensed channels are same with TABLE V. We evaluate the performance of methods with the change of the number of Wi-Fi networks. The contained Wi-Fi networks are illustrated in TABLE VI, and the corresponding parameters of the Wi-Fi networks are separately listed in TABLE VII. Wi-Fi network 1, 2, 3, 4, 5, 6, 7 occupied unlicensed channels are channel 1, 2, 3, 4, 5, 6, 7 respectively.

For the CCOT method, since it aims to satisfy SBS users' data rate demands and they are satisfied when the number of

TABLE VII
THE PARAMETERS OF WI-FI NETWORKS

	The number of stations	Data packet size /Bytes	Throughput /Mbps
Wi-Fi network 1	5	1500	30.853
Wi-Fi network 2	10	1200	27.699
Wi-Fi network 3	15	1000	25.016
Wi-Fi network 4	20	800	21.873
Wi-Fi network 5	25	500	15.976
Wi-Fi network 6	30	500	15.848
Wi-Fi network 7	35	200	7.6240

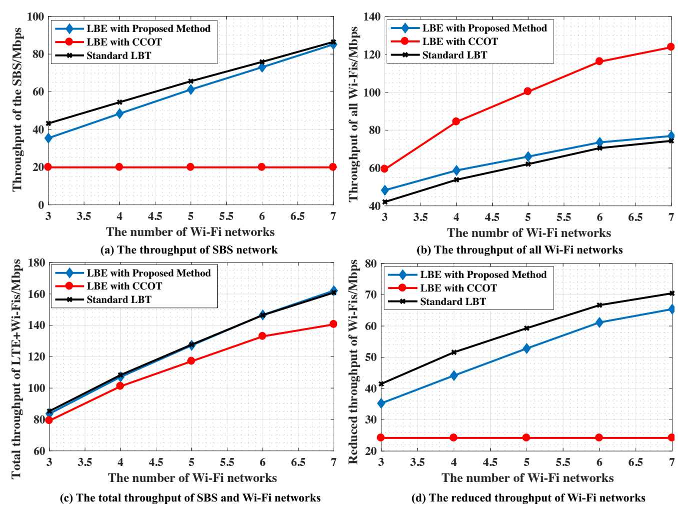


Fig. 11. The throughput of networks in the second simulation environment.

Wi-Fi networks is 2, the throughput of SBS and the reduced throughput of Wi-Fi networks will not change with the number of Wi-Fi networks shown in Fig. 11 a, d. However, the throughput of all Wi-Fi networks and the total throughput of SBS and Wi-Fi networks will increase with the increase in the number of Wi-Fi networks. What's more, since the throughput of SBS of the continuous COT method is minimized, its throughput of Wi-Fi networks is the largest shown in Fig. 9 b.

The COT values of our proposed method on channels 1-7 are $5ms, 6ms, 10ms, 13ms, 13ms, 13ms, 13ms$ respectively. These values are the maximum values of satisfying the fairness criterion. Comparing with the standard LBT method, which

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVT.2019.2940123, IEEE Transactions on Vehicular Technology

sets COT of all channels to $10ms$, the throughput of the SBS of our proposed method is smaller than it and the throughput of all Wi-Fi networks of our proposed methods is larger than it when the number of Wi-Fi networks is 3, but the gap gradually decreases with the increase of the number of Wi-Fi networks illustrated in Fig. 11 a and b. In a channel, the increase of COT of the SBS will increase the throughput of the SBS, at the same time the throughput of the Wi-Fi network using the channel to transmit data will be reduced. However, the increased throughput of SBS is larger than the reduced throughput of Wi-Fi networks. Therefore, in Fig. 11 c, at first the total throughput of the standard LBT method is larger than our proposed method, but the throughput of our proposed method is gradually larger than the standard LBT method with the increase of the number of Wi-Fi networks. The total throughput of these two methods is larger than the CCOT method.

We use Wi-Fi network 2 to evaluate the influence of the number of Wi-Fi networks on the fairness illustrated in Fig. 12. For our proposed method, the COT of channel 2 is $6ms$. It is the maximum value of satisfying the fairness criterion and will not change with the number of Wi-Fi networks. In the standard LBT method the COT is fixed to $10ms$, therefore, the fairness is not satisfied in channel 2 and at the same time it will not change with the number of Wi-Fi networks. For the CCOT method, it occupies channel 2 $2ms$ to satisfy the SBS users' COT demands, hence, the fairness is satisfied. What's more, since SBS users' demands do not change, the throughput of Wi-Fi network 2 will not be influenced with the change of the number of Wi-Fi networks in these mechanisms. In conclusion, the LBE mechanism using our proposed method optimizes the throughput of SBS while ensuring the fairness.

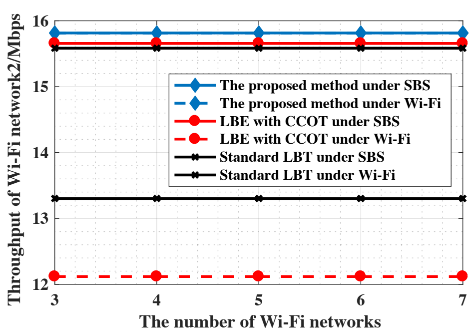


Fig. 12. The fairness evaluation of Wi-Fi network 2 in the second simulation environment.

VI. Related Work

Nowadays there are lots of work studying the LBE analytical framework for the coexistence of Wi-Fi and LTE networks. [19] characterizes when the 3GPP notion of fairness in the coexistence is achievable. [22] explores the impact of energy detection threshold on Wi-Fi and LTE coexistence. [23] establishes different Markov chain models for Cat. 4 LBT scheme, Cat. 3 LBT scheme classified by 3GPP [8], Wi-Fi DCF, and evaluates the performance of LTE, Wi-Fi in terms of throughput and transmission delay. All these works aim to analyze the performance of the coexistence network without considering performance optimization. To improve the performance of the coexistence LTE and Wi-Fi networks, most existing papers propose to adjust access parameters (the contention window size of the back-off procedure, energy detection threshold of the CCA check) of LBE.

Adjusting the contention window: [24] proposes a mathematical framework to find the optimal size of cellular base stations, which maximizes the total throughput of both networks while satisfying the required throughput of each network. In [25] LTE adjusts the CW size to an appropriate value using sensing, calculating and comparing the slot utilization in a period of time to gain higher throughput. [26] proposes a Fair Downlink Traffic Management (FDTM) scheme to tune the minimum CW value of LTE which is fixed in the back-off procedure of the Cat. 3 LBT scheme and assign feasible weights for LTE with different traffic loads to ensure the throughput fairness for Wi-Fi networks. In [27], the SBS adaptively adjusts the back-off window size according to the available licensed spectrum bandwidth and the Wi-Fi traffic load to satisfy the quality-of-service requirements of small cell users and minimize the collision probability of Wi-Fi users.

Optimizing the energy detection threshold: [28] applies the optimal stopping theory that LBE should stop listening and transmitting once the channel quality exceeds an optimized energy detection threshold to study the throughput optimal transmission strategy. [29] enhances the overall system capacity and satisfies the 3GPP fairness criterion from the aspect of spectrum reuse. It combines the advantages of transmission start time alignment and energy detection threshold adaption into a unified access framework, in which the alignment reference interval is adaptively adjusted to control the channel-access probability for LAA and Wi-Fi systems.

The aforementioned papers ignore the influence of the parameter COT in LBT on the throughput of network. [11] points out that the conventional LBT mechanism fixing the Channel Occupation Time is inefficient under the varying traffic load in Wi-Fi and LTE systems. It proposes an adaptive LBE-LBT mechanism composed of on-off adaptation for the COT of LTE and short-long adaptation for idle time. [30] proposes a hybrid MAC protocol that combines the best features of LBE MAC and FBE MAC. By jointly optimizing the sleep period and the CW size of LTE, the best co-existing performance regarding the total network throughput and the throughput fairness of LTE and Wi-Fi can be achieved, with minimal reservation overhead. Besides fairness, [31] proposes a model for the distribution of the MAC delays experienced by the Wi-Fi packets and LTE frames, which can be used to dynamically adjust the LBE parameters including the duration of LTE frames, the average initial LTE contention window not only to achieve channel-time fairness but also to guarantee MAC-delay bounds with a specific probability. However, since there is not a fairness standard reached a consensus, these papers use different standards to evaluate fairness. None of them considers the fairness criterion used in our paper. The fairness is the LTE network does not impact the performance of the Wi-Fi network on a carrier more than an additional Wi-Fi network operating on the same carrier and offering the same level of traffic load of the LTE network.

VII. Conclusion

In this paper, we proposed a channel occupation time adjustment method for the LBE mechanism to maximize the throughput of LTE while ensuring the fairness coexistence and satisfying the LTE users' data rate demands. In the process of calculating the throughput of LTE and Wi-Fi networks on a coexistence unlicensed channel, we propose a new method considering the synchronization of SBS on licensed and unlicensed spectrum. In addition, to satisfy fairness, we propose a virtual Wi-Fi network construction method to deal with the situation that the Wi-Fi network offering the same level of traffic load of the LTE network does not exist on the carrier. The NS3 simulation results first prove our proposed throughput calculation method for the LTE and Wi-Fi coexistence network is valid, and then, it demonstrates that the proposed method optimizes the throughput of the SBS network and ensures fairness. In the future, we will study how to adjust the size of contention window or jointly adjust the size of contention window and COT to maximize the throughput of LTE network while satisfying the used fairness criterion.

References

[1] C. V. N. Index, "Global mobile data traffic forecast update, 2015–2020," *Cisco white paper*, 2016.
[2] L. Zhu, C. Zhang, C. Xu, X. Du, R. Xu, K. Sharif, and M. Guizani, "Prif: A privacy-preserving interest-based forwarding scheme for social internet of vehicles," *IEEE Internet of Things Journal*, vol. 5, no. 4, pp. 2457–2466, 2018.
[3] 3GPP, "Radio frequency system scenarios," Technical Specification Group Radio Access Networks, TR 25.942, 2011, version 10.0.0.
[4] HUAWEI, "U-lte: unlicensed spectrum utilization of lte," May, 2017.
[5] N. Rupasinghe and İ. Güvenç, "Licensed-assisted access for wifi-lte coexistence in the unlicensed spectrum," in *2014 IEEE Globecom Workshops (GC Wkshps)*. IEEE, 2014, pp. 894–899.
[6] H. Zhang, S. Chen, X. Li, H. Ji, and X. Du, "Interference management for heterogeneous networks with spectral efficiency improvement," *IEEE Wireless Communications*, vol. 22, no. 2, pp. 101–107, 2015.
[7] Y. Jian, C.-F. Shih, B. Krishnaswamy, and R. Sivakumar, "Coexistence of wi-fi and laa-lte: Experimental evaluation, analysis and insights," in *2015 IEEE international conference on communication workshop (ICCW)*. IEEE, 2015, pp. 2325–2331.
[8] 3GPP, "Study on licensed-assisted access to unlicensed spectrum," Technical Specification Group Radio Access Networks, TR 36.889, 2015, version 13.0.0.
[9] S. Zinno, G. Di Stasi, S. Avallone, and G. Ventre, "On a fair coexistence of lte and wi-fi in the unlicensed spectrum: A survey," *Computer Communications*, vol. 115, pp. 35–50, 2018.
[10] 3GPP, "Evolved universal terrestrial radio access physical layer procedures," TS 36.213, 2017, version 13.0.0.
[11] C. K. Kim, C. S. Yang, and C. G. Kang, "Adaptive listen-before-talk (lbt) scheme for lte and wi-fi systems coexisting in unlicensed band," in *2016 13th IEEE Annual Consumer Communications & Networking Conference (CCNC)*. IEEE, 2016, pp. 589–594.
[12] H. He, H. Shan, A. Huang, L. X. Cai, and T. Q. Quek, "Proportional fairness-based resource allocation for lte-u coexisting with wi-fi," *IEEE Access*, vol. 5, pp. 4720–4731, 2016.
[13] C. Cano and D. J. Leith, "Coexistence of wifi and lte in unlicensed bands: A proportional fair allocation scheme," in *2015 IEEE international conference on communication workshop (ICCW)*. IEEE, 2015, pp. 2288–2293.
[14] M. Khabazian, O. Kubbar, and H. Hassanein, "A fairness-based preemption algorithm for lte-advanced," in *2012 GLOBECOM*. IEEE, 2012, pp. 5320–5325.
[15] Z. Guan and T. Melodia, "Cu-lte: Spectrally-efficient and fair coexistence between lte and wi-fi in unlicensed bands," in *IEEE INFOCOM*. IEEE, 2016, pp. 1–9.
[16] Y. Huang, Y. Chen, Y. T. Hou, W. Lou, and J. H. Reed, "Recent advances of lte/wifi coexistence in unlicensed spectrum," *IEEE Network*, vol. 32, no. 2, pp. 107–113, 2017.
[17] Q. Wang, Z. Gao, X. Du, and L. Zhu, "An optimal lte-u access method for throughput maximization and fairness assurance," in *2018 IEEE 37th International Performance Computing and Communications Conference (IPCCC)*. IEEE, 2018, pp. 1–8.
[18] A. Garcia-Saavedra, P. Patras, V. Valls, X. Costa-Perez, and D. J. Leith, "Orla/olaa: Orthogonal coexistence of laa and wifi in unlicensed spectrum," *IEEE/ACM Transactions on Networking*, vol. 26, no. 6, pp. 2665–2678, 2018.
[19] M. Mehrnoush, S. Roy, V. Sathya, and M. Ghosh, "On the fairness of wi-fi and lte-laa coexistence," *IEEE Transactions on Cognitive Communications and Networking*, vol. 4, no. 4, pp. 735–748, 2018.
[20] G. Bianchi, "Performance analysis of the ieee 802.11 distributed coordination function," *IEEE Journal on selected areas in communications*, vol. 18, no. 3, pp. 535–547, 2000.
[21] L. Giupponi, T. Henderson, B. Bojovic, and M. Miozzo, "Simulating lte and wi-fi coexistence in unlicensed spectrum with ns-3," *arXiv preprint arXiv:1604.06826*, 2016.
[22] M. Mehrnoush, V. Sathya, S. Roy, and M. Ghosh, "Analytical modeling of wi-fi and lte-laa coexistence: Throughput and impact of energy detection threshold," *IEEE/ACM Transactions on Networking (TON)*, vol. 26, no. 4, pp. 1990–2003, 2018.
[23] Y. Gao, X. Chu, and J. Zhang, "Performance analysis of laa and wifi coexistence in unlicensed spectrum based on markov chain," in *GLOBECOM*. IEEE, 2016, pp. 1–6.
[24] Y. Song, K. W. Sung, and Y. Han, "Coexistence of wi-fi and cellular with listen-before-talk in unlicensed spectrum," *IEEE Communications Letters*, vol. 20, no. 1, pp. 161–164, 2015.
[25] F. Hao, C. Yongyu, H. Li, J. Zhang, and W. Quan, "Contention window size adaptation algorithm for laa-lte in unlicensed band," in *2016 International Symposium on Wireless Communication Systems (ISWCS)*. IEEE, 2016, pp. 476–480.
[26] Y. Li, T. Zhou, Y. Yang, H. Hu, and M. Hamalainen, "Fair downlink traffic management for hybrid laa-lte/wi-fi networks," *IEEE Access*, vol. 5, pp. 7031–7041, 2016.
[27] R. Yin, G. Yu, A. Maaref, and G. Y. Li, "Lbt-based adaptive channel access for lte-u systems," *IEEE Transactions on Wireless Communications*, vol. 15, no. 10, pp. 6585–6597, 2016.
[28] N. Wei, X. Lin, W. Li, Y. Xiong, and Z. Zhang, "Throughput optimal listen-before-talk for cellular in unlicensed spectrum," in *ICC*. IEEE, 2017, pp. 1–6.
[29] C. S. Yang, C. K. Kim, J.-M. Moon, S.-H. Park, and C. G. Kang, "Channel access scheme with alignment reference interval adaptation (aria) for frequency reuse in unlicensed band lte: Fuzzy q-learning approach," *IEEE Access*, vol. 6, pp. 26 438–26 451, 2018.
[30] S. Khairy, L. X. Cai, Y. Cheng, Z. Han, and H. Shan, "A hybrid-lbt mac with adaptive sleep for lte laa coexisting with wi-fi over unlicensed band," in *GLOBECOM*. IEEE, 2017, pp. 1–6.
[31] G. J. Sutton, R. P. Liu, and Y. J. Guo, "Delay and reliability of load-based listen-before-talk in laa," *IEEE Access*, vol. 6, pp. 6171–6182, 2017.

Qian Wang is working toward the Ph.D. degree at the Beijing University of Posts and Telecommunications (BUPT), Beijing, China. Her current research interests include wireless networks and opportunistic communications.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVT.2019.2940123, IEEE Transactions on Vehicular Technology

Xiaojiang Du is currently a Tenured Professor with the Department of Computer and Information Sciences, Temple University, Philadelphia, PA, USA. His research interests are wireless communications, wireless networks, security and systems. He has authored more than 350 journal and conference papers in these areas, and a book. He has been awarded over 6 million U.S. dollars research grants from the U.S. National Science Foundation, Army Research Office, Air Force Research Laboratory, NASA, the State of Pennsylvania, and Amazon. He is a Life Member ACM. He is on the editorial boards of three international journals.

Zhipeng Gao received the Ph.D. degree from the Beijing University of Posts and Telecommunications (BUPT), Beijing, China, in 2007. He is currently a Professor with the State Key Laboratory of Networking and Switching Technology, BUPT, Beijing, China. His research interests are wireless networks, edge computing and blockchain. He presides over a series of key research projects on network and service management, including the projects supported by the National Natural Science Foundation and the National High-Tech Research and Development Program of China. He received eight provincial scientific and technical awards.

Mohsen Guizani (S'85-M'89-SM'99-F'09) received the B.S. (with distinction) and the M.S. degrees in electrical engineering, the M.S. and Ph.D. degrees in computer engineering from Syracuse University, Syracuse, NY, USA, in 1984, 1986, 1987, and 1990, respectively. He is currently a Professor with the Computer Science and Engineering Department, Qatar University, Qatar. Previously, he served in different academic and administrative positions at the University of Idaho, Western Michigan University, University of West Florida, University of Missouri-Kansas City, University of Colorado-Boulder, and Syracuse University. He is the author of nine books and more than 500 publications in refereed journals and conferences. He guest edited a number of Special Issues in IEEE journals and magazines. His research interests include wireless communications and mobile computing, computer networks, mobile cloud computing, security, and smart grids. He is currently the Editor-in-chief of the IEEE NETWORK magazine, on the editorial boards of several international technical journals, and the Founder and Editor-in-chief of *Wireless Communications and Mobile Computing journal* (Wiley). He was also a member, Chair, and General Chair of a number of international conferences. Throughout his career, he received three teaching awards and four research awards. He also received the 2017 IEEE Communications Society WTC Recognition Award as well as the 2018 AdHoc Technical Committee Recognition Award for his contribution to outstanding research in wireless communications and ad-hoc sensor networks. He was the Chair of the IEEE Communications Society Wireless Technical Committee and the Chair of the TAOS Technical Committee. He was the IEEE Computer Society Distinguished Speaker and is currently the IEEE ComSoc Distinguished Lecturer. He is a Senior Member of ACM.