LBT-Based Adaptive Channel Access for LTE-U Systems

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***Abstract*— Driven by the demand for more radio spectrum resources, mobile operators are looking to exploit the unlicensed spectrum as a complement to the licensed spectrum. LTE-unlicensed (LTE-U), also referred to as licensed-assisted access by the third generation partnership project, is an extension of the LTE standard operating on the unlicensed spectrum. To realize LTE-U, its coexistence with Wi-Fi systems is the main challenge and must be addressed. In this paper, a listen-before-talk access mechanism featuring an adaptive distributed control function protocol is adopted for the small base stations (SBSs), whereby the backoff window size is adaptively adjusted 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. Meanwhile, both licensed and unlicensed spectrum bands are jointly allocated to optimize spectrum efficiency. An admission control mechanism is further developed for the SBS to limit collision with Wi-Fi traffic. Extensive simulation results show that the proposed schemes achieve fair and harmonious coexistence between LTE-U small cells and the surrounding Wi-Fi service sets and substantially outperform baseline non-adaptive channel access mechanisms in the unlicensed spectrum.**

***Index Terms*— LTE-Unlicensed, LAA, small cell, Wi-Fi, LBT, adaptive channel access.**

I. Introduction

IT IS forecasted in [1] that the request on mobile data will increase by 10-fold by 2019. To deal with this challenge, many new techniques have been proposed to improve data rate in the *fifth generation* (5G) wireless systems [2]. However, the scarcity of the licensed spectrum for cellular networks is still the main bottleneck for further performance improvement. As a result, exploiting the unlicensed bands currently used by Wi-Fi systems becomes a promising option [3], [4].

Manuscript received April 30, 2015; revised November 20, 2015 and March 29, 2016; accepted June 17, 2016. Date of publication June 29, 2016; date of current version October 7, 2016. This work was supported in part by the National Natural Science Foundation Program of China under Grant 61301143, in part by a Research Gift from Huawei Technologies Canada, Co., Ltd., and in part by the Natural Science and Technology Specific Major Project of China under Grant 2015ZX03001031. The associate editor coordinating the review of this paper and approving it for publication was Y. Chen.

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Digital Object Identifier 10.1109/TWC.2016.2586467

Recently, the Federal Communications Commission (FCC) has released an additional 295 MHz bandwidth in the 5 GHz *Unlicensed National Information Infrastructure* (U-NII) band. Then there is over 400 MHz unlicensed spectrum for public. On the other hand, Wi-Fi is the most popular and successful technique to provide wireless service on the unlicensed bands in a local area [5]. With low cost and high data rate, Wi-Fi systems have been already the dominant player on all unlicensed bands in 2.4 and 5 GHz. However, spectrum efficiency in Wi-Fi systems is pretty low, especially under the overloaded conditions. In contrast, *long-term evolution* (LTE) has more efficient resource management and error control techniques. Therefore, allowing LTE to use the unlicensed bands, called *LTE-unlicensed* (LTE-U), not only alleviates spectrum scarcity of the cellular system, but also improves the spectrum efficiency on the unlicensed bands. One of the critical challenges for the LTE-U system is how to deal with interference to the existing Wi-Fi users and ensure harmonious.

Several channel access schemes for the LTE-U systems, based on the duty cycle method or the *listen-before-talk* (LBT) mechanism, have been proposed to deal with the coexistence issue. The schemes based on the duty cycle method [6], [7] periodically turns the LTE signal on and off by using *almost blank subframes* (ABSs) on unlicensed bands. In this case, Wi-Fi users can only access the unlicensed spectrum when the LTE signal is off. Therefore, the LTE-U system dominates the utilization of the unlicensed bands. For the methods based on the LBT mechanism [8]–[12], the *small base station* (SBS) and *small cell users* (SUs) sense the unlicensed bands before using them. Since the *distributed coordination function* (DCF) employed in Wi-Fi systems complies with the LBT rule, fair coexistence between Wi-Fi and LTE can be achieved. The *frame based equipment* (FBE) and the *load based equipment* (LBE) schemes have been proposed in [13], where the exponential backoff method in the DCF has been replaced by either a static or a uniformly distributed backoff scheme. However, from [14], neither of them leads to an optimal and fair coexistence between the SBS and the Wi-Fi APs due to the lack of adaptivity.

Although using the unlicensed spectrum in LTE-U can release certain pressure on the spectrum shortage, it is still not enough to satisfy the future 10-fold mobile data increase. Some cutting-edge techniques, such as massive *multiple-input multiple-output* (MIMO) and ultra dense small cell system, have been developed to improve the spectrum efficiency. Therefore, another important issue for LTE-U is how to efficiently integrate the licensed and unlicensed bands to improve the spectrum efficiency. Conventionally, SBS only considers spectrum efficiency while satisfying the QoS of SUs on the licensed bands. However, when using the unlicensed bands at the SBS, the impact to Wi-Fi systems should also be taken into consideration. Intuitively, the more the unlicensed bands are used by the SBS, the higher the spectrum efficiency will be achieved on the unlicensed bands. However, this will cause the performance degradation of the Wi-Fi users. Therefore, there exists an intrinsic tradeoff between the spectrum efficiency and the impact to the Wi-Fi users in the LTE-U system.

In order to use unlicensed bands, the Wi-Fi interface is assumed to be integrated into the SBSs in [15]–[17]. However, the unlicensed bands are still used based on the Wi-Fi protocols. In [18], fair coexistence between LTE and Wi-Fi on the unlicensed bands has been investigated using a stochastic geometry modeling approach where an LBT protocol is applied at the SBS. It is shown therein that LTE-U can improve the spectrum efficiency, but does not necessarily guarantee a fair coexistence with Wi-Fi on the unlicensed spectrum. In [19], the LTE and Wi-Fi coexistence has been studied and the performance degradation of the Wi-Fi system due to interference from the LTE system has been analyzed. In [20], the unlicensed bands are split into two non-overlapping sets for SBSs and Wi-Fi *access points* (AP)s, respectively, which has addressed the fairness and QoS to certain extent. A traffic balancing scheme between licensed and unlicensed bands has been proposed for the cellular network when the SBS serves only one user [21]. The unlicensed band sharing scheme by operators has been investigated in a game theoretic setting in [22].

In this paper, we develop adaptive channel access schemes to address the fair coexistence and joint spectrum management in LTE-U systems.[1] Since the *3rd Generation Partnership Project* (3GPP) has identified LBT as a working assumption in the process of standardizing a global solution for the LTE-U systems, we enforce a similar LBT requirement on our proposed access mechanism. However, instead of adopting the standard exponential backoff scheme as in the Wi-Fi systems, the backoff window size for the SBSs will be adaptively adjusted based on the available licensed bandwidth and the Wi-Fi traffic load. When the SBS only shares the unlicensed band with single Wi-Fi AP, the SBS will determine the minimum unlicensed bandwidth requirement to satisfy the QoS of SUs through jointly optimizing the transmission power, licensed and unlicensed spectrum allocation. To exploit more unlicensed bands and, at the same time, mitigate serious impact to some individual Wi-Fi APs, the SBS may share the unlicensed bands with multiple Wi-Fi APs. In this scenario, the impact from the SBS to different Wi-Fi APs should be balanced.

Even though the collision probability to the Wi-Fi users is minimized in the proposed schemes, it may be still intolerable for the Wi-Fi system if too many SUs need to be served on the unlicensed bands. Therefore, an *admission control* (AC) scheme is designed for the SBS to restrict the number of served SUs. As a result, the collision probability is upper-bounded to a threshold to guarantee the fair coexistence between the Wi-Fi APs and the SBS.

[1]Part of this work has been published in IEEE Globecom 2015 [23]. In this journal version, we include proofs, derivations, and the adaptive channel access scheme design for the scenario that the SBS shares unlicensed bands with multiple Wi-Fi APs that are omitted in the conference version.

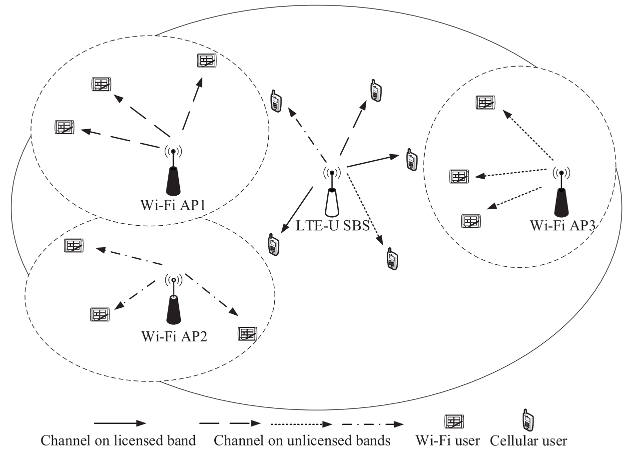


Fig. 1. System model.

In brief, our main contributions in this paper can be summarized as follows.

1. The transmission power, licensed and unlicensed bands are jointly considered when designing the adaptive schemes for the SBS to guarantee the fair coexistence while optimizing the spectrum efficiency.
2. The impact to the Wi-Fi APs is balanced based on their collision probability thresholds when the SBS shares the unlicensed bands with multiple Wi-Fi APs.
3. The fundamental tradeoff between the spectrum efficiency and the Wi-Fi performance is revealed when the proposed schemes are applied.

It is noteworthy that Wi-Fi performance has been thoroughly studied in [24] and a simple, but accurate, analytical model to compute the Wi-Fi throughput has been proposed. In this paper, we focus on the coexistence between Wi-Fi and LTE-U.

The rest of the paper is organized as follows. In Section II, the system model for the SBS sharing the unlicensed bands with the Wi-Fi APs and the corresponding performance metric are introduced. Adaptive channel access schemes for the SBS are developed when the SBS shares the unlicensed bands with one Wi-Fi AP and with multiple Wi-Fi APs in Sections III and IV, respectively. In Section V, an admission control scheme is proposed. In Section VI, we evaluate the performance of the proposed schemes by simulation. Finally, the paper is concluded in Section VII.

II. System Model

As shown in Fig. 1, we consider K Wi-Fi APs in the coverage of a single SBS. Denote the set of K Wi-Fi APs as $\mathcal{K}$. The SBS can use both licensed and unlicensed bands to support the downlink transmission to SUs. Meanwhile, Wi-Fi APs can only use the unlicensed bands to serve Wi-Fi users and different Wi-Fi APs will use different unlicensed bands to avoid strong co-channel interference. Assuming Wi-Fi AP

k serves n_k users. To enable SBS's access to the unlicensed bands, the LBT mechanism is adopted in the SBS to compete for the unlicensed bands with the Wi-Fi users. We start with a simple scenario that the SBS shares the unlicensed band with one Wi-Fi AP, and then extend to the scenario with multiple Wi-Fi APs.

A. DCF Mechanism

According to the IEEE 802.11 standard, Wi-Fi users compete for an unlicensed channel based on the DCF mechanism. With DCF, an exponential backoff scheme with the minimum backoff window size, $W_F^{(k)}$, and the maximum contention stage, $m_F^{(k)}$, is adopted in Wi-Fi AP k. From [24], the stationary probability, τ_k, that users served by Wi-Fi AP k transmit a packet can be written as

$$\tau_k = \frac{2 \times (1 - 2p_F^{(k)})}{(1 - 2p_F^{(k)})(W_F^{(k)} + 1) + p_F^{(k)} W_F^{(k)} (1 - (2p_F^{(k)})^{m_F^{(k)}})}, \tag{1}$$

where $p_F^{(k)}$ is the collision probability when the packet is transmitted on the channel. Accordingly, the channel access probability of the SBS to the unlicensed band used by Wi-Fi AP k can be written as

$$\eta_B^{(k)}(W_B^{(k)}) = \frac{2(1 - 2p_B^{(k)})}{(1 - 2p_B^{(k)})(W_B^{(k)} + 1)}, \tag{2}$$

where $p_B^{(k)}$ is the collision probability experienced by the SBS when competing the unlicensed bands with users served by Wi-Fi AP k, and $W_B^{(k)}$ is the corresponding backoff window size. It should be noted that we do not use the contention stage in the SBS. In the proposed schemes, $W_B^{(k)}$ will be adjusted adaptively to control the channel access probability of the SBS on the unlicensed bands.

Then, the collision probabilities for users served by Wi-Fi AP k and the SBS can be expressed as

$$p_F^{(k)} = 1 - (1 - \eta_B^{(k)})(1 - \tau_k)^{n_k - 1}, \tag{3}$$

and

$$p_B^{(k)} = 1 - (1 - \tau_k)^{n_k}, \tag{4}$$

respectively.

B. Performance Metric

The throughput of Wi-Fi AP k is defined as the fraction of successful packet transmission time, which can be written as [24]

$$H_k = \frac{P_T^{(k)} P_S^{(k)} \mathbf{E}\{L\}}{(1 - P_T^{(k)})\delta + P_T^{(k)} P_S^{(k)} Q_s^{(k)} + P_T^{(k)}(1 - P_S^{(k)}) Q_c^{(k)}}, \tag{5}$$

where $P_T^{(k)}$ and $P_S^{(k)}$ are the probability that there is at least one transmission on the unlicensed band and that of successful transmission, respectively, and can be expressed as

$$P_T^{(k)} = 1 - (1 - \tau_k)^{n_k}(1 - \eta_B^{(k)}), \tag{6}$$

and

$$P_S^{(k)} = \frac{n_k \tau_k (1 - \tau_k)^{n_k - 1}(1 - \eta_B^{(k)})}{P_T^{(k)}}, \tag{7}$$

$\mathbf{E}\{\cdot\}$ is an expectation function, L is the packet payload size, $Q_s^{(k)}$ is the average channel occupied time because of a successful transmission, and $Q_c^{(k)}$ is the average channel busy time sensed by a user within the coverage of Wi-Fi AP k because of collision [24]. Although we use the saturation throughput in (5), which is the maximum load that the system can carry in stable conditions, the proposed schemes in this paper can be extended to the unsaturation situation, using the same method as [24] in [25].

According to (1), (5), (6), and (7), higher collision probability means lower Wi-Fi throughput. Therefore, the collision probability, $p_F^{(k)}$, can measure the impact from the SBS to the Wi-Fi AP k on the unlicensed band. If it exceeds a predefined threshold value, $\bar{\theta}_k$, the fair coexistence between the SBS and the Wi-Fi AP k can not be guaranteed. Since it is related to the channel access probability of the SBS, $\eta_B^{(k)}$, which is decided by the backoff window size, $W_B^{(k)}$, we can control the collision probability by adjusting $W_B^{(k)}$.

On the SBS side, the conditional successful transmission probability, when competing with Wi-Fi AP k, is

$$\hat{P}_S^{(k)} = \frac{\eta_B^{(k)}(1 - \tau_k)^{n_k}}{P_T^{(k)}}. \tag{8}$$

Therefore, the achievable time fraction on the unlicensed band for the SBS when competing with Wi-Fi AP k can be written as

$$S_U^{(k)} = \hat{P}_S^{(k)} P_T^{(k)}. \tag{9}$$

The achievable data rate of SU i consists of two parts. The first part is achieved on the licensed band, and can be written as

$$R_L^{(i)} = c_L^{(i)} \log\left(1 + \frac{p_L^{(i)} h_L^{(i)}}{c_L^{(i)} N_0}\right), \tag{10}$$

where $c_L^{(i)}$ is the fraction of the licensed bandwidth allocated to SU i, $p_L^{(i)}$ is the transmission power allocated on the licensed band for SU i, $h_L^{(i)}$ is the channel power gain between the SBS and SU i on the licensed band, and N_0 is the noise power.

The second part is achieved on the unlicensed bands. Since the SBS shares the unlicensed bands with the Wi-Fi APs in a *time-division multiple access* (TDMA) way, its data rate can be written as

$$R_U^{(i)} = \sum_{k=1}^{K} s_U^{(k,i)} B_U^{(k)} \log\left(1 + \frac{p_U^{(k,i)} h_U^{(k,i)}}{B_U^{(k)} N_0}\right), \tag{11}$$

where $s_U^{(k,i)}$ is the time fraction allocated to SU i on the unlicensed band for Wi-Fi AP k, $p_U^{(k,i)}$ is the transmission power allocated on the unlicensed band for SU i, $h_U^{(k,i)}$ is the channel power gain between the SBS and SU i on the unlicensed band, and $B_U^{(k)}$ is the unlicensed bandwidth used by Wi-Fi AP k.

From the above discussion, the achievable data rate at SU i is given by

$$R_i = R_L^{(i)} + R_U^{(i)}. \tag{12}$$

In the paper, we assume that $p_L^{(i)}$ can be dynamically controlled while $p_U^{(k,i)}$ is fixed due to the regulations for the utilization of the unlicensed bands [27].

According to (1), (5), (6), (7), and (9), we have the following proposition, proved in Appendix A.

Proposition 1: Sharing unlicensed spectrum with LTE-U system will bring extra collision probability to the Wi-Fi users and decrease the Wi-Fi throughput.

Therefore, the collision probability, $p_F^{(k)}$, can measure the impact from the SBS to the Wi-Fi AP k on the unlicensed band. If it exceeds a predefined threshold value, $\bar{\theta}_k$, the fair coexistence between the SBS and the Wi-Fi AP k can not be guaranteed. Since it is related to the channel access probability of the SBS, $\eta_B^{(k)}$, which is decided by the backoff window size, $W_B^{(k)}$, we can control the collision probability by adjusting $W_B^{(k)}$.

III. Sharing With One Wi-Fi AP

In this section, an adaptive channel access scheme for the SBS is developed in the scenario with only one Wi-Fi AP, i.e. $K = 1$. Therefore, the index for the Wi-Fi AP, k, is dropped in this section since there is only one Wi-Fi AP. We adjust the backoff window size of the SBS based on the achievable licensed band and the Wi-Fi traffic load to satisfy the QoS of SUs.

The data rate requirement of SU i, $R_i(t)$, should be guaranteed in every time slot t[2]

$$R_i(t) \geq r_i, \tag{13}$$

where r_i is the minimum data rate requirement for SU i. Since there is only one Wi-Fi AP considered in this case, $R_i(t)$ can be written as

$$R_i(t) = c_L^{(i)}(t) \log\left(1 + \frac{p_L^{(i)}(t) h_L^{(i)}(t)}{c_L^{(i)}(t) N_0}\right) + s_U^{(i)}(t) B_U \log\left(1 + \frac{p_U^{(i)}(t) h_U^{(i)}(t)}{B_U N_0}\right). \tag{14}$$

On the other hand, in order to guarantee the coexistence between the SBS and the Wi-Fi AP, the collision probability experienced by the Wi-Fi users should be less than a threshold, $\bar{\theta}$.

A. Collision Probability Minimization

From the above discussion, minimizing the impact brought by the SBS on the unlicensed band is equivalent to minimizing the collision probability to the Wi-Fi users. Therefore, the optimization problem can be formulated as

$$\min_{\pi} \mathbf{E}(p_F(t)) = \min_{\pi} \lim_{T\to\infty} \frac{1}{T} \sum_{t=1}^{T} p_F(t), \tag{15}$$

subject to

$$R_i(t) \geq r_i, \forall i \in \mathcal{U}, \quad \forall t, \tag{15a}$$
$$\sum_{i\in\mathcal{U}} c_L^{(i)}(t) \leq C_L(t), \quad \forall t, \tag{15b}$$
$$\sum_{i\in\mathcal{U}} s_U^{(i)}(t) \leq S_U(t), \quad \forall t, \tag{15c}$$
$$\sum_{i\in\mathcal{U}} p_L^{(i)}(t) \leq P_T, \quad \forall t, \tag{15d}$$
$$p_L^{(i)}(t) \geq 0; \forall i \in \mathcal{U}, \quad \forall t, \tag{15e}$$
$$s_U^{(i)}(t) \geq 0, \; c_L^{(i)}(t) \geq 0, \quad \forall t, \tag{15f}$$

where $\mathcal{U}$ is the index set of the SUs, (15b) and (15c) ensure that the maximum licensed bandwith and the total transmission time on the unlicensed band should be no more than $C_L(t)$ and $S_U(t)$ at each time slot, respectively, (15d) is the total transmit power constraint on the licensed band, and π is the policy defined as

$$\pi = \{\eta_B(t), \{c_L^{(i)}(t), s_U^{(i)}(t)\}_{i\in\mathcal{U}}, \{p_L^{(i)}(t)\}_{i\in\mathcal{U}}\}_t. \tag{16}$$

According to (8) and (9), the available unlicensed band, $S_U(t)$, in (15c) is a function of the channel access probability of the SBS, η_B, as

$$S_U(t) = \eta_B(t)(1 - \tau(t))^n. \tag{17}$$

The objective function defined in optimization problem (15) is an expectation of the collision probability experienced by the Wi-Fi users with respect to the channel power gains of the SUs on licensed and unlicensed bands. The state of the system in time slot t can be defined by the channel power gains of SUs on the licensed and unlicensed bands, $\left(h_L^{(i)}(t), h_U^{(i)}(t)\right)$, $\forall i \in \mathcal{U}$. In each time slot t, the SBS needs to decide how to allocate the transmission power, licensed and unlicensed spectrum jointly based on the channel power gains of the SUs on licensed and unlicensed bands, $\left(h_L^{(i)}(t), h_U^{(i)}(t)\right)$, $\forall i \in \mathcal{U}$, to satisfy SUs' data rate requirements. After these, the collision probability experienced by the Wi-Fi users can be calculated according to the analysis present in Section II. Since the objective function in problem (15) is an expectation function of a random value with respect to the channel power gains of SUs, it is a stochastic optimization problem as defined in [26]. Solving the stochastic optimization problem needs the system state transition probabilities, which are impossible to obtain in advance here. Fortunately, with the following lemma, as proved in Appendix B, the problem in (15) can be transformed into a deterministic optimization problem.

Lemma 1: The stochastic problem in (15) *is equivalent to the following deterministic optimization problem for each time slot t, $t \in \{1, \cdots, T\}$,*

$$\min_{\pi} p_F(t), \tag{18}$$

subject to (15a)*,* (15b)*,* (15c)*,* (15d)*,* (15e)*, and* (15f)*.*

The objective function in (18) is to minimize the collision probability experienced by the Wi-Fi users at each time slot t. Based on (3), the channel collision probability for Wi-Fi users, p_F, monotonically increases with the channel access

[2]In this work, one time slot refers to one LTE frame with a duration of 10ms.

probability, η_B, of the SBS. Therefore, higher channel access probability of the SBS will incur higher collision probability. On the contrary, according to (17), the available unlicensed band at the SBS monotonically increases with η_B. Therefore, minimizing the collision probability to the Wi-Fi users is equivalent to minimizing the required unlicensed band at the SBS. Then, problem (18) can be further transformed to

$$\min_{\{c_L^{(i)}, s_U^{(i)}, p_L^{(i)}\}_{i\in\mathcal{U}}} \sum_{i\in\mathcal{U}} s_U^{(i)}, \tag{19}$$

subject to

$$R_i \geq r_i, \quad \forall i \in \mathcal{U}, \tag{19a}$$

$$\sum_{i\in\mathcal{U}} c_L^{(i)} \leq C_L, \tag{19b}$$

$$\sum_{i\in\mathcal{U}} p_L^{(i)} \leq P_T, \tag{19c}$$

$$p_L^{(i)} \geq 0, \quad \forall i \in \mathcal{U}, \tag{19d}$$

$$c_L^{(i)} \geq 0, \quad s_U^{(i)} \geq 0, \quad \forall i \in \mathcal{U}. \tag{19e}$$

It should be noted that we have dropped the symbol t in (19). The objective function in (19) is linear. Furthermore, with the following lemma proved in Appendix C, it is a convex optimization problem.

Lemma 2: R_i in constraint (19a) *is concave and* (19) *is a convex optimization problem.*

As a result, the global optimal solution to (19) can be found by conventional Lagrangian multiplier method and based on the *Karush-Kuhn-Tucker* (KKT) conditions, the necessary condition for not using unlicensed bands in the SBS can be derived in the following theorem, provided in Appendix D.

Theorem 1: $s_U^{(i)} = 0$, $\forall i \in \mathcal{U}$, if the power and the licensed bandwidth allocation satisfies

$$\frac{p_L^{(i)} h_L^{(i)}}{p_L^{(i)} h_L^{(i)} + c_L^{(i)} N_0} = \frac{r_i}{c_L^{(i)}} - \frac{\beta}{\lambda_i}, \tag{20}$$

$$p_L^{(i)} = c_i\left(\frac{\lambda_i}{\mu} - \frac{N_0}{h_L^{(i)}}\right)^+, \tag{21}$$

where $(x)^+ = \max(x, 0)$*,* $\lambda_i = \frac{1}{\log\left(1+\frac{p_U^{(i)} h_U^{(i)}}{B_U N_0}\right)}$*, β is the Lagrangian multiplier related to the achievable licensed bandwidth constraint in* (19b)*, and μ is the Lagrangian multiplier related to the power constraint in* (19c)*.*

As we have explained in Appendix D, Theorem 1 can be used to judge whether the unlicensed bandwidth is required to serve SUs at the SBS. If there exist $p_L^{(i)}$ and $c_L^{(i)}$ to fulfill conditions (20) and (21), then the licensed bandwidth is enough to satisfy the QoS of SUs. Otherwise, the SBS has to use the unlicensed band to guarantee the QoS of SUs.

After solving problem (19), the minimum required time fraction on the unlicensed band, $S_U = \sum_{i\in\mathcal{U}} s_U^{(i)}$, for the SBS to satisfy the QoS of the SUs can be determined. Substituting S_U into (17), we can obtain the relation between channel access probabilities of the Wi-Fi users, τ, and the SBS, η_B. With this relation, (1) and (3) become two nonlinear equations with two unknown variables, i.e. the channel access probability of Wi-Fi users, τ, and the collision probability, p_F. We can numerically solve this problem. In Appendix E, we prove that there exists a unique solution for this nonlinear system.

TABLE I

ADAPTIVE CHANNEL ACCESS ALGORITHM FOR SINGLE WI-FI AP SCENARIO

Algorithm 1

1: In each time slot t, SBS first decides how much licensed bands, C_L, can be used;
2: **if** C_L is enough to serve all SUs in $\mathcal{U}$ (using Theorem 1) **then**
3: Set $W_B = \infty$;
4: **else**
5: Find the optimal values $\{p_L^{(i)}, c_L^{(i)}, s_U^{(i)}\}_{i\in\mathcal{U}}$ for problem (19);
6: **end if**
7: **return** The optimal values $\{p_L^{(i)}, c_L^{(i)}, s_U^{(i)}\}_{i\in\mathcal{U}}$;
8: Calculate $S_U = \sum_i s_U^{(i)}$ with the optimal values achieved in STEP 7. Estimate the number of Wi-Fi users on the unlicensed band with the method introduced in [28];
9: Evaluate the collision probability, p_F, and channel access probability of the SBS, η_B, based on (1), (3), and (17);
10: Calculate the parameter W_B with η_B according to (2);

B. Adaptive Channel Access Scheme

Based on the above analysis, an adaptive channel access scheme for the LTE-U SBS can be developed, which is shown in Table I. In the first step, the SBS determines whether the achievable licensed spectrum is enough to serve all SUs based on Theorem 1. If not, the SBS needs to evaluate the required unlicensed band by solving (19). Then, the SBS calculates the window size and provides the downlink transmission to the SUs. In step 8, the SBS needs to know the number of active Wi-Fi users. Since the LBT mechanism is adopted in the scheme, the SBS can monitor the unlicensed spectrum. Therefore, the conventional methods applied in Wi-Fi APs to estimate the number of Wi-Fi users can be used in the SBS. For example, in [28], the relationship between the collision probability and the number of Wi-Fi users has been derived. Then, a scheme based on an extended Kalman filter coupled with a change detection mechanism has been developed, which can estimate the number of Wi-Fi users with high accuracy. To decease the computational complexity, an adaptive estimator of the number of the competing Wi-Fi users has been proposed based on sequential Monte Carlo methods in [29]. Since the stochastic optimization problem in (15) is converted into a deterministic convex optimization problem (18), the computational complexity is $O(|\mathcal{U}|^3)$, where $|\mathcal{U}|$ is the number of CUs.

It is noteworthy that the collision probability brought by the SBS maybe exceed the collision probability threshold, $\bar{\theta}_k$, due to a large number of SUs. Therefore, admission control in the SBS is necessary to guarantee a fair coexistence with the Wi-Fi system, which will be further studied in Section V.

IV. SHARING WITH MULTIPLE WI-FI APS

As indicated in Section III, some SUs can not be served by the SBS due to limited available unlicensed band from one Wi-Fi AP. To serve more SUs, the SBS should exploit more unlicensed band. A natural way is to let the SBS share the unlicensed bands with multiple Wi-Fi APs. Therefore, in this section, a channel adaptive access scheme will be developed for the SBS to share the unlicensed bands with multiple Wi-Fi APs.

The new challenge for the SBS sharing the unlicensed bands with multiple Wi-Fi APs is how to balance the collision probability among different Wi-Fi APs. To address this issue, the optimization problem becomes to minimize the maximum collision probability among all Wi-Fi APs, which can be written as

$$\min_{\tilde{\pi}} \ \mathbf{E}(\max\{\alpha_1 p_F^{(1)}(t), \cdots, \ \alpha_K p_F^{(K)}(t)\}) \tag{22}$$

$$= \min_{\tilde{\pi}} \lim_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T} \max_k\{\alpha_k p_F^{(k)}(t)\}, \tag{23}$$

subject to

$$R_i(t) \geq r_i(t), \quad \forall i \in \mathcal{U}, \ \forall t, \tag{23a}$$

$$\sum_{i\in\mathcal{U}} c_L^{(i)}(t) \leq C_L(t), \quad \forall t, \tag{23b}$$

$$\sum_{i\in\mathcal{U}} s_U^{(k,i)}(t) \leq S_U(t), \quad \forall k \in \mathcal{K}, \ \forall t, \tag{23c}$$

$$\sum_{i\in\mathcal{U}} p_L^{(i)}(t) \leq P_T, \quad \forall t, \tag{23d}$$

$$p_L^{(i)}(t) \geq 0, \quad \forall i \in \mathcal{U}, \ \forall t, \tag{23e}$$

$$s_U^{(k,i)}(t) \geq 0, \quad c_L^{(i)}(t) \geq 0, \ \forall t, \ \forall k \in \mathcal{K}, \ i \in \mathcal{U}, \tag{23f}$$

where $\tilde{\pi}$ is the policy defined as

$$\tilde{\pi} = \{\tilde{\eta}(t), \{c_L^{(i)}(t), s_U^{(k,i)}(t)\}_{i\in\mathcal{U},k\in\mathcal{K}}, \{p_L^{(i)}(t)\}_{i\in\mathcal{U}}\}_t, \tag{24}$$

α_k is the weight factor corresponding to Wi-Fi AP k, which can be used to balance the collision probability among Wi-Fi APs. This problem has the same constraints as (15) except that the constraint (15c) is changed to (23c) to aggregate the unlicensed bands from different Wi-Fi APs.

Using the same technique as in Section III-A, we can transform the problem in (22) into the following deterministic problem

$$\min_{\{c_L^{(i)}, s_U^{(k,i)}, p_L^{(i)}\}_{i\in\mathcal{U},k\in\mathcal{K}}} \max_k\{\eta_1 \textstyle\sum_{i\in\mathcal{U}} s_U^{(1,i)}, \cdots, \eta_K \sum_{i\in\mathcal{U}} s_U^{(K,i)}\}, \tag{25}$$

subject to (19b), (19c), (19c), (19d), and

$$c_L^{(i)} \log\left(1 + \frac{p_L^{(i)} h_L^{(i)}}{c_L^{(i)} N_0}\right) + \sum_{k=1}^{K} s_U^{(k,i)} B_U^{(k)} \log\left(1 + \frac{p_U^{(k,i)} h_U^{(k,i)}}{B_U^{(k)} N_0}\right) \geq r_i, \ \forall i \in \mathcal{U}, \tag{25a}$$

$$s_U^{(k,i)}(t) \geq 0, \quad c_L^{(i)} \geq 0, \ i \in \mathcal{U}, \ \forall k \in \mathcal{K}, \tag{25b}$$

where $\eta_k, \ \forall k \in \mathcal{K}$, is the weight factor on the utilization of the unlicensed bands from different Wi-Fi APs, which corresponds to $\alpha_k, \ \forall k \in \mathcal{K}$, and can be obtained by the collision threshold value, $\bar{\theta}_k$. First, based on $\bar{\theta}_k$, the maximum available unlicensed band, $S_U^{(k)}$, can be obtained (the details will be explained in Section V). Then, the channel access probability of the SBS on the unlicensed band for Wi-Fi AP k, η_k, can be determined as $\eta_k = S_U^{(K)} \Big/ \sum_{k\in\mathcal{K}} S_U^{(k)}$.

TABLE II

ADAPTIVE CHANNEL ACCESS ALGORITHM FOR THE MULTIPLE WI-FI APS SCENARIO

Algorithm 2

1: Initialize $\beta_k = \frac{\bar{S}_U^{(k)}}{\sum_{j=1}^{K} \bar{S}_U^{(j)}}$, $\forall k \in \mathcal{K}$, based on the collision probability threshold of Wi-Fi AP k, $\bar{\theta}_k, \ k \in \mathcal{K}$;
2: In each time slot t, SBS first decides how much licensed bands, C_L, can be used;
3: **if** C_L is enough to serve all SUs in $\mathcal{U}$ **then**
4: Set $W_B = \infty$;
5: **else**
6: With C_L, formulate the optimization problem as (27), and then use the Lagrangian multiplier method to solve it;
7: **end if**
8: **return** The optimal values $\{p_L^{(i)}, c_L^{(i)}, s_U^{(k,i)}\}_{i\in\mathcal{U}, \ k\in\mathcal{K}}$;
9: Calculate $S_U^{(i)} = \sum_i s_U^{(i)}$ with the optimal values achieved in STEP 8. Estimate the number of Wi-Fi users on the unlicensed band with the method introduced in [28]. Evaluate the collision probability, $p_F^{(k)}, \ k \in \mathcal{K}$, and the channel access probability of the SBS, $\eta_B^{(k)}, \ k \in \mathcal{K}$, based on the (1), (3) and (17);
10: Calculate the parameter $W_B^{(k)}$ with $\eta_B^{(k)}$ for each k according to (2);

To solve (25), a new scalar variable x is introduced to replace the max$\{\cdot\}$ function in (25),

$$x = \max_k\{\beta_1 \textstyle\sum_{i\in\mathcal{U}} s_U^{(1,i)}, \cdots, \beta_K \sum_{i\in\mathcal{U}} s_U^{(K,i)}\}. \tag{26}$$

Then the problem in (25) is equivalent to

$$\min_{x,\{c_L^{(i)}, s_U^{(k,i)}, p_L^{(i)}\}_{i\in\mathcal{U},k\in\mathcal{K}}} x, \tag{27}$$

subject to (19b), (19c), (19c), (19d), (19e), (25a), and

$$x \geq \beta_k \textstyle\sum_{i\in\mathcal{U}} s_U^{(k,i)}, \quad \forall k \in \mathcal{K}. \tag{27a}$$

Since, the summation of convex functions is still convex, function in (25a) is convex. Moreover, as both the objective function in (27) and the new constraint in (27a) are linear, problem (27) becomes convex. Therefore, the Lagrangian multiplier or dual method can be applied to find its optimal solution.

Based on the above discussion, the adaptive channel access scheme for the SBS sharing with multiple Wi-Fi APs is described in Table II. Similar to Algorithm 1, the SBS needs to judge whether the licensed bandwidth is enough to serve all SUs. However, different from the single Wi-Fi scenario, Theorem 1 no longer exists due to the presence of multiple Wi-Fi APs. Therefore, the following convex optimization problem is used to testify whether the licensed bandwidth is enough

$$\max_{\{c_L^{(i)}\geq 0, \ p_L^{(i)}\geq 0\}_{i\in\mathcal{U}}} \sum_{i\in\mathcal{U}} R_i, \tag{28}$$

subject to (25a), (19b), and (19c).

If there is a solution to (28), then the licensed bandwidth, C_L, is enough to serve SUs. Otherwise, the unlicensed bands are required at the SBS. Then, by solving the problem (27), the unlicensed bands collected from different Wi-Fi APs can be obtained. Accordingly, the backoff window size $W_B^{(k)}$, for $k \in \mathcal{K}$, can be derived in the SBS, as indicated in Table II. Since there are multiple Wi-Fi APs, the computational complexity becomes $O\left((K\,|\mathcal{U}|)^3\right)$. It is noteworthy that in both scheme I and II, the SBS does not need to run the optimization in each time slot unless the number of Wi-Fi users served by Wi-Fi APs changes

It is noteworthy that if the collision probability to any Wi-Fi AP is over the threshold, then the collision probability to the remaining Wi-Fi APs is also cross the threshold due to the balance property of Algorithm 2. Furthermore, Algorithm 2 also faces the same problem as Algorithm 1 that the collision probability may exceed the threshold if the number of SUs is too large. To deal with the issue, an admission control scheme will be designed in the next section.

V. Admission Control

Before selecting SUs to serve at the SBS, the available unlicensed bandwidth from Wi-Fi APs should be decided first. Based on the collision probability threshold for SU k, $\bar{\theta}_k$, the maximum achievable time fraction for the SBS on different unlicensed bands can be derived. To do so, first, by replacing the collision probability of users served by Wi-Fi AP k, $p_F^{(k)}$, with $\bar{\theta}_k$ in (1), the channel access probability for the Wi-Fi users, τ_k, can be derived. Then, substituting τ_k into (3) and replacing $p_F^{(k)}$ with $\bar{\theta}_k$ in (3), we can derive the channel access probability of the SBS on the unlicensed band for the Wi-Fi AP k, $\eta_B^{(k)}$. With τ_k and $\eta_B^{(k)}$, the transmission probability in (6) and the conditional successful probability for the SBS, $\hat{P}_S^{(k)}$, in (8) can be obtained. Finally, with (9), the available unlicensed band, $S_U^{(k)}$, for the SBS from Wi-Fi AP k can be obtained.

Then, we need to select the subset of SUs to serve at the SBS with the available licensed and unlicensed bandwidths. To maximize the number of SUs served by the SBS, the optimization problem can be formulated as

$$\max_{\{I_i, c_L^{(i)}, s_U^{(k,i)}, p_L^{(i)}\}_{i\in\mathcal{U}}} \sum_{i\in\mathcal{U}} I_i, \tag{29}$$

subject to (19b), (19c), (19d), and

$$R_i - I_i r_i \geq 0, \quad \forall i \in \mathcal{U}, \tag{29a}$$

$$\sum_{i\in\mathcal{U}} s_U^{(k,i)} \leq S_U^{(k)}, \quad \forall k \in \mathcal{K}, \tag{29b}$$

$$I_i \in \{0, 1\}, \quad \forall i \in \mathcal{U}, \tag{29c}$$

where I_i is an integer variable, $I_i = 1$ when SU i is selected, $I_i = 0$ otherwise, (29a) guarantees that the data rate of the selected SU is no less than that it requests, (29b) is to guarantee that the collision probability to the Wi-Fi users is less than $\bar{\theta}$. Obviously, (29) is a *mixed-integer nonlinear programming* (MINLP) and it is hard to find a global optimal solution.

To find a sub-optimal solution to (29), we first relax the binary variable, I_i, to be continuous in [0, 1]. Constraint (29a) is the difference of a concave function and a linear function and therefore is concave. The remaining constraints are all linear. Therefore, the relaxed problem is convex. After finding the optimal solution by the Lagrangian multiplier method, we order the SUs in $\mathcal{U}$ by the value, I_i, from high to low, $\tilde{\mathcal{U}} = \{SU_{(1)}, \cdots, SU_{(i)}, \cdots, SU_{(N)}\}$. Then the bisection method is applied to find the maximum number of SUs served by the SBS, which can be described in Table III.

TABLE III
ADMISSION CONTROL

Algorithm 3

if $p_F^{(k)} > \bar{\theta}_k, \forall k \in \mathcal{K},$ **then**
    Based on the collision probability threshold, $\bar{\theta}_k,\ k \in \mathcal{K}$, obtain the maximum achievable bandwidth, $S_U^{(k)}, k \in \mathcal{K}$, on different unlicensed bands for the SBS;
end if
With the available C_L and the $S_U^{(k)}, k \in \mathcal{K}$, formulate the optimization problem as (29). Use the relaxation method to obtain a sub-optimal solution for $I_i,\ i \in \mathcal{U}$;
Initialize $N_{\min} = 0$, $N_{\max} = N$, counter $j = 1$, $M(j) = N_{\max}$, and $M_{\text{temp}} = 0$;
while $M(j) - M_{\text{temp}} \geq 2$ **do**
    $M_{\text{temp}} = M(j)$, $j = j + 1$;
    Set $M(j) = \lceil \frac{N_{\min}+N_{\max}}{2} \rceil$;
    Select $\{SU_{(1)}, \cdots, SU_{M(j)}\}$ as the user set served by the SBS and solve the problem in (28);
    if There is a solution **then**
        $N_{\min} = M(j)$;
    else
        $N_{\max} = M(j)$;
    end if
end while
return $N^* = M_{\text{temp}}$ and select SU group, $\{SU_{(1)}, \cdots, SU_{(N^*)}\}$;

VI. Simulation Results

In this section, simulation results are presented to verify the proposed algorithms. In the simulation, the radius of the small cell is set to be 50 m and SUs are randomly located in its coverage. We assume that the channels between the SUs and the SBS are with block fading. The other major simulation parameters are listed in Table IV. Furthermore, we assume that the Wi-Fi users have the same type of traffic and the traffic load of Wi-Fi system changes with the number of the Wi-Fi users. We evaluate the proposed schemes from three aspects. First, the impact of the LTE-U SBS to the Wi-Fi system is evaluated. Then, the system throughput on the unlicensed band and the Wi-Fi packet delay are examined. Third, the performance of Algorithms 1 and 2 with AC is compared. Two additional access schemes are also presented for comparison, which are the *non-adaptive channel access scheme* (NAS) where the SBS uses the same backoff scheme as the Wi-Fi users, and the *exclusive Wi-Fi scheme* (EWS) where the SBS is replaced by a Wi-Fi AP, which is a Wi-Fi network.

A. Sharing Unlicensed Band With Single Wi-Fi AP

Fig. 2 demonstrates the fraction of unlicensed band occupation versus the number of served SUs for different licensed spectrum bandwidth when the SBS only shares the unlicensed band with one Wi-Fi AP. Obviously, when the available bandwidth of the licensed spectrum is fixed, the desired unlicensed band in the SBS will increase as the number of the SUs increases to satisfy the QoS of the SUs. On the other hand, when the number of SUs is fixed, more available licensed bandwidth means less utilization on the unlicensed band for the SBS as shown in the figure. Therefore, there is a tradeoff between the available licensed band and the required unlicensed band in the SBS.

TABLE IV
SIMULATION PARAMETERS

Parameters	Value
Wi-Fi packet payload	12000bits
MAC header of Wi-Fi packet	192bits
PHY header of Wi-Fi packet	224bits
SIFS	$16\mu s$
DIFS	$34\mu s$
ACK	$112\text{bits} + 224\text{bits}$
Channel bit rate for Wi-Fi	300Mbps
Wi-Fi backoff window size $W^{(WF)}$	$16\mu s$
Wi-Fi maximum backoff stage $m^{(WF)}$	6
Wi-Fi slot time size, σ	$20\mu s$
Collision probability threshold, $\bar{\theta}$	0.35
Unlicensed bandwidth	20MHz
Total transmission power on licensed band $P_T^{(l)}$	35dBm
Transmission power on unlicensed band $p_{k,i}^{(u)}$	23dBm
AWGN noise power	-174dBm/Hz
Data rate requirement of SUs	15Mbps
Path loss model on licensed band (dB)	$-15.3 - 37.6\log_{10}(d(m))$
Path loss model on unlicensed band (dB)	$-15.3 - 50\log_{10}(d(m))$

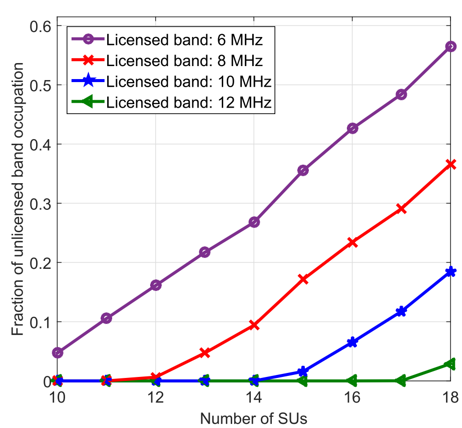


Fig. 2. Utilization of unlicensed band in SBS.

Without implementing the AC in Algorithm 1, the collision probability brought to the Wi-Fi system is shown in Fig. 3 when the available licensed band is 8 MHz. From the figure, as the number of SUs increases, more unlicensed band are required to satisfy the QoS of SUs, which will exceed the collision probability threshold to the Wi-Fi users.

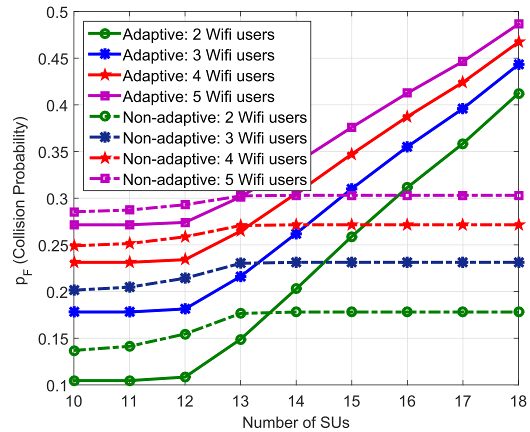


Fig. 3. Collision probability to Wi-Fi users without AC by Algorithm 1.

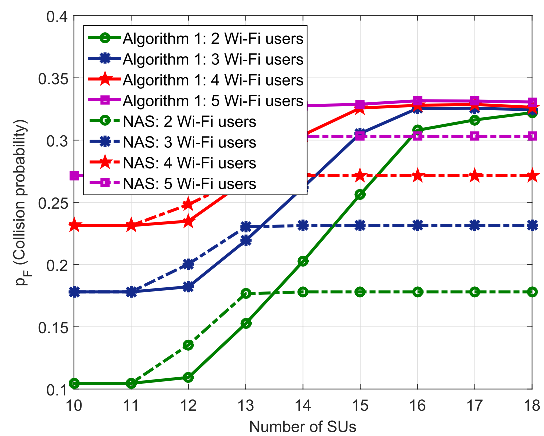


Fig. 4. Collision probability to Wi-Fi users by Algorithm 1.

With the AC in Algorithm 1, the collision probability to the Wi-Fi users can be properly controlled as shown in Fig. 4. From the figure, there are three typical situations for the SBS using the unlicensed band. When the number of SUs is between 10 to 11, the available licensed bandwidth is enough to satisfy the QoS of the SUs. Then, the collision probability experienced by the Wi-Fi users has nothing to do with the SBS. When the number of the SUs is between 12 to 15, the SBS requires the unlicensed band to serve the SUs and the collision probability brought to the Wi-Fi users is within the threshold. When the number of the SUs is over 16, the request on the unlicensed band in the SBS is so large that only some SUs are selected by the SBS to keep the collision probability within the threshold. Therefore, the unlicensed band can be adaptively used according to the achievable licensed bandwidth and the Wi-Fi traffic load. Moreover, when fewer Wi-Fi users are served by the Wi-Fi AP, more unlicensed spectrum can be exploited at the SBS to serve more SUs. When only 2 Wi-Fi users are active in the system, the SBS can serve 18 SUs which is the most. On the other hand, when 5 Wi-Fi users are present in the system, the SBS can provide service to 14 SUs, which is the least. Therefore, the unlicensed band can be adaptively used according to the achievable licensed bandwidth and the Wi-Fi traffic load in the proposed schemes.

Fig. 5 shows the achievable throughput on the unlicensed band by Algorithm 1, the NAS, and the EWS, respectively. From the figure, the throughput by the EWS decreases with the

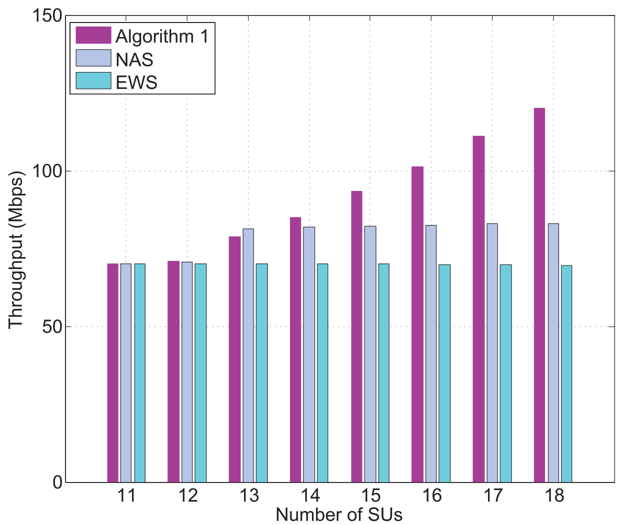


Fig. 5. Throughput on unlicensed band.

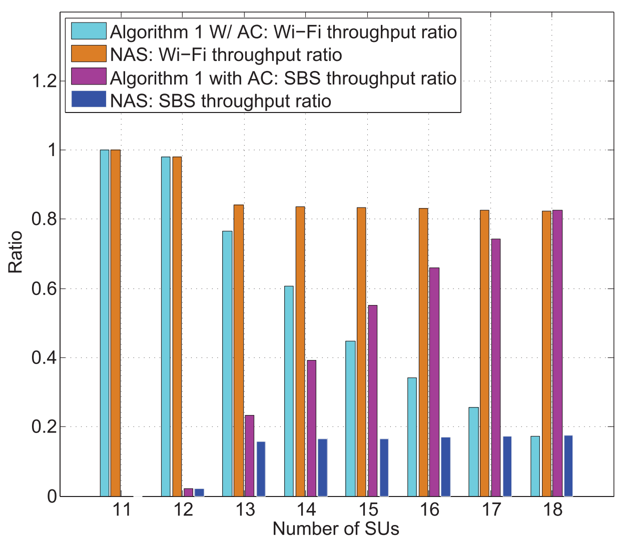


Fig. 6. Throughput ratio of Wi-Fi and SBS on unlicensed band.

number of the SUs. On the contrary, the throughput by Algorithm 1 increases with the number of SUs. This is because, as the number of SUs increases, the unlicensed band utilization in the SBS increases, which brings more user diversity gain. However, it will result in lower Wi-Fi throughput as shown in Fig. 6, which plots the contribution of the Wi-Fi to the system throughput with different SU numbers. From Fig. 6, as the number of SUs increases, the contribution of the SBS to the system throughput on the unlicensed band increases in Algorithm 1. Therefore, there is an inherent tradeoff between the spectrum efficiency and the Wi-Fi throughput.

Moreover, from Fig. 5, the throughput of Algorithm 1 is less than that of the NAS when the number of SUs is 13. This is because that the SBS only takes the unlicensed band just enough to satisfy the QoS of SUs due to its adaptive characteristic. Therefore, when the number of the SUs is 13, the unlicensed band used by the SBS in Algorithm 1 is less than that in the NAS. As a result, the throughput on the unlicensed band achieved by the NAS is higher than that of Algorithm 1.

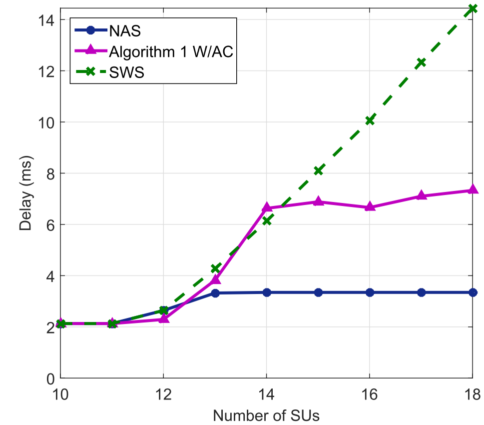


Fig. 7. Wi-Fi packet delay.

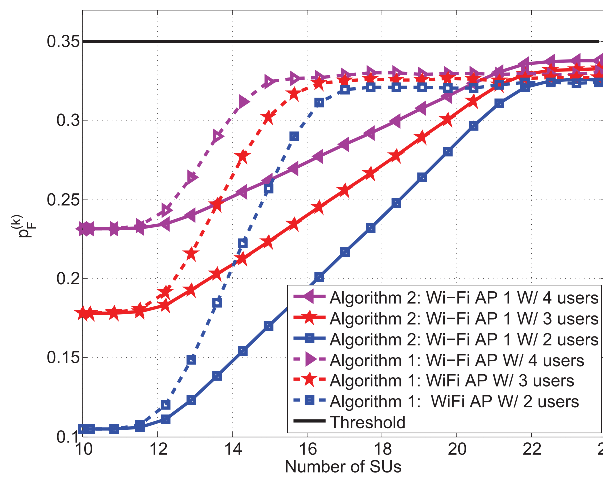


Fig. 8. Collision probability comparison between Algorithm 1 and Algorithm 2 with AC.

Fig. 7 shows the packet delay performance in the Wi-Fi system when Algorithm 1 with AC, the NAS, and the EWS are applied. As the number of SUs increases, the packet delay of EWS increases as well. However, the Wi-Fi packet delay experienced by both Algorihm 1 and the NAS tends to be constant. This is because that the collision probability is controlled to be less than the threshold by the AC and is due to the constant backoff window size for the NAS. Even though the Wi-Fi packet delay in Algorithm 1 is worse than that by the NAS, the achievable spectrum efficiency on unlicensed band by Algorithm 1 is better than that by the NAS, as shown in Fig. 5. Therefore, there is a tradeoff between the Wi-Fi packet delay and the spectrum efficiency on the unlicensed bands.

B. Single Wi-Fi AP v.s. Multiple Wi-Fi APs

Assuming there are three Wi-Fi APs around the SBS and each serves different numbers of users, where Wi-Fi AP 1, 2, and 3 serves 2, 3, and 4 users, respectively. For a fair comparison, we also evaluate the performance of Algorithm 1 in the above environment. Fig. 8 compares the collision probability to the Wi-Fi users in the two schemes. From the figure, the maximum number of the SUs served by the SBS is 17 in Algorithm 1 when the Wi-Fi AP serves 2 users. However, the collision probability for 3 Wi-Fi APs with Algorithm 2 does not reach the bound even when the number of SUs is as many as 22. Therefore, the SBS can provide service to

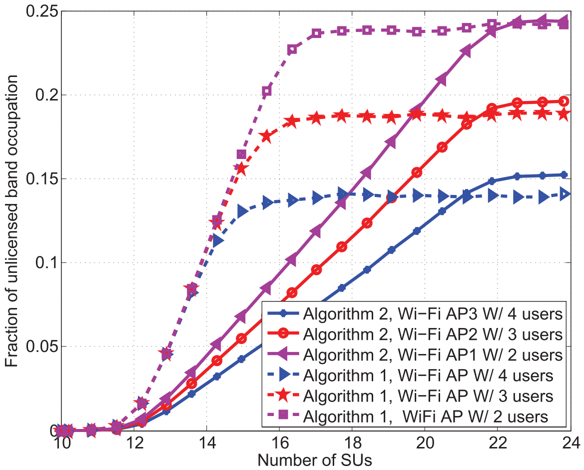


Fig. 9. Occupation on unlicensed bands by the SBS in Algorithm 1 and Algorithm 2 with AC.

more SUs by Algorithm 2 with the cost of high computational complexity. On the other hand, similar to Fig. 4, the SBS can use more unlicensed spectrum to serve more SUs when fewer Wi-Fi users are active. Therefore, the SBS can exploit the unlicensed band adaptively in the proposed schemes based on the Wi-Fi traffic to guarantee the fair coexistence.

Furthermore, the collision probabilities experienced by three Wi-Fi APs are close to each other and do not exceed the threshold value as shown in Fig. 8. Therefore, the impact to different Wi-Fi APs brought by the LTE-U SBS is properly balanced in Algorithm 2. To make this point more clear, the fraction of unlicensed band occupied by the SBS from different Wi-Fi APs in Algorithm 2 are compared with that in Algorithm 1 in Fig. 9. From the figure, the time fraction of the unlicensed bands occupied by the SBS in Algorithm 2 converges to fixed values to guarantee the fair coexistence with different Wi-Fi APs as the number of SUs increases. On the other hand, the convergence values are close to those in Algorithm 1 as shown in Fig. 9. Therefore, the collision probabilities to different Wi-Fi APs are properly balanced in Algorithm 2.

VII. Conclusions

In the paper, we have developed adaptive channel access schemes for the SBS to access unlicensed bands with the help of the LBT mechanism. We have considered two cases that the SBS shares the unlicensed band with only one Wi-Fi AP and multiple Wi-Fi APs, respectively. The SBS accesses the unlicensed band adaptively according to the Wi-Fi traffic on the unlicensed band and the available licensed bandwidth. When the SBS is allowed to share the unlicensed bands with multiple APs, the fairness on the collision probability to different Wi-Fi APs is considered. The collision probability brought by the SBS to Wi-Fi APs may still exceed a threshold due to a large number of SUs served by the SBS. Therefore, an admission control scheme is proposed to deal this problem. Through simulation, the proposed adaptive channel access schemes can be used to ensure fair coexistence between LTE and Wi-Fi on the unlicensed bands. Furthermore, the inherent tradeoff between the spectrum efficiency of the unlicensed bands and the Wi-Fi system performance is also revealed.

Appendix A
Proof for Proposition 1

The Wi-Fi throughput expression in (5) is equivalent to

$$H_k = \frac{\mathbf{E}\{L\}}{Q_S^{(k)} - Q_c^{(k)} + \frac{\delta(1-P_T^{(k)})/P_T^{(k)} + Q_c^{(k)}}{P_S^{(k)}}}, \tag{30}$$

where $Q_S^{(k)}$, $Q_c^{(k)}$, and δ are constants. Based on (6) and (7), the third item in the denominator of (30) can be rewritten as

$$\begin{aligned}\frac{\delta(1-P_T^{(k)})/P_T^{(k)} + Q_c^{(k)}}{P_S^{(k)}} &= \delta \cdot \left[\frac{Q_c^{(k)}}{\delta} \cdot \frac{1}{n\tau_k(1-\tau_k)^{n_k-1}(1-\eta_B^{(k)})}\right. \\ &\quad \left. - \frac{(1-\tau_k)}{n_k\tau_k} \cdot \left(\frac{Q_c^{(k)}}{\delta} - 1\right)\right]. \end{aligned} \tag{31}$$

Based on the equation (3), we also have the following expression

$$p_F^{(k)} = 1 - (1-\eta_B^{(k)})(1-\tau_k)^{n_k-1}, . \tag{32}$$

Substituting (32) into (31), we have

$$\begin{aligned}&\frac{\delta(1-P_T^{(k)})/P_T^{(k)} + Q_c^{(k)}}{P_S^{(k)}} \\ &= \delta \cdot \left[\frac{Q_c^{(k)}}{\delta} \cdot \frac{1}{n\tau_k(1-p_F^{(k)})} - \frac{(1-\tau_k)}{n_k\tau_k} \cdot \left(\frac{Q_c^{(k)}}{\delta} - 1\right)\right]. \end{aligned} \tag{33}$$

Therefore, based on (33), if the collision probability, $p_F^{(k)}$, to the Wi-Fi users increases due to sharing the unlicensed band with LTE-U systems, the value of (33) will increase. Since (33) is part of the denominator of (5), Wi-Fi throughput will decrease as the value of (33) increases. Therefore, the collision probability brought to the Wi-Fi users by the LTE-U systems would jeopardize the Wi-Fi performance and it can be used to evaluate the impact brought to the Wi-Fi by the LTE-U system on unlicensed spectrum.

Appendix B
Proof of Equivalence

Based on the Jason inequality, we have

$$\min_{\pi} \mathbf{E}\{p_F(t)\} \le \mathbf{E}\{\min_{\pi} p_F(t)\}, \tag{34}$$

where $\mathbf{E}\{\min_{\pi} p_F(t)\}$ equals to minimizing the collision probability in each time slot t, $\min_{\pi} p_F(t)$, $\forall t \in \{1, \cdots, T\}$.

Assume that $\pi^\star$ is the optimal solution to $\mathbf{E}\{\min_{\pi} p_F(t)\}$ and $\{\hat{p}_F(1), \cdots, \hat{p}_F(T)\}$ is the optimal sequence value obtained by $\pi^\star$. The item in the sequence must satisfy

$$\hat{p}_F(t) = \min_{\pi^\star} p_F(t), \quad \forall t \in \{1, \cdots, T\}. \tag{35}$$

Since the collision probability experienced by the Wi-Fi AP monotonically decreases with the time fraction occupied by the SBS on the unlicensed band, according to (35) and the definition of constraints in (15), we have

$$\pi^\star: \ R_i(t) = r_i, \quad \forall i \in \mathcal{U}, \ \forall t, \tag{36}$$

when the policy $\pi^\star$ is applied.

On the other hand, assuming that π' is the optimal solution to $\min_{\pi} \mathbf{E}\{p_F(t)\}$ and the achievable optimal value sequence is $\{\tilde{p}_F(1), \cdots, \tilde{p}_F(T)\}$, then, with definition π' and the constraints in (15), we have

$$\pi': \ R_i(t) \geq r_i, \quad \forall i \in \mathcal{U}, \ \forall t. \tag{37}$$

Since the SU's data rate monotonically increases with $s_U^{(i)}$ on the unlicensed band and the policy would not change the system state (including the channel state, Wi-Fi traffic on unlicensed band, and the achievable licensed band for the SBS), we get

$$\tilde{p}_F(t) \geq \hat{p}_F(t), \quad \forall t. \tag{38}$$

Then, we have

$$\min_{\pi'} \mathbf{E}\{p_F(t)\} \geq \mathbf{E}\{\min_{\pi^\star} p_F(t)\}. \tag{39}$$

Comparing (39) with (34), we conclude

$$\min_{\pi'} \mathbf{E}\{p_F(t)\} \triangleq \mathbf{E}\{\min_{\pi^\star} p_F(t)\}, \tag{40}$$

in our case.

As we mentioned above, the collision probability experienced by the Wi-Fi AP monotonically increases with unlicensed bandwidth occupied by the SBS. Therefore, minimizing the collision probability is equivalent to minimizing the unlicensed band occupation time at the SBS, as expressed in (19).

APPENDIX C
PROOF OF CONVEXITY

Define a function

$$f(x, y) = -x \log(1 + \frac{y}{x}). \tag{41}$$

We can derive the Hessian of $f(x, y)$ is

$$\mathbf{H} = \begin{vmatrix} \frac{y^2/x}{(x+y)^2} & -\frac{y}{(x+y)^2} \\ -\frac{y}{(x+y)^2} & \frac{x}{(x+y)^2} \end{vmatrix}, \tag{42}$$

which has the eigenvalues

$$\lambda_1 = 0, \quad \lambda_2 = \frac{x^2 + y^2}{x^3 + 2x^2 y + x y^2}. \tag{43}$$

Obviously, the eigenvalues of $\mathbf{H}$ are either greater than or equal to zero when $x \geq 0$. Therefore, the function $f(x, y)$ is a convex function when $x \geq 0$. Furthermore, the function,

$$s_U^{(i)} B_U \log(1 + \frac{p_u^{(i)} h_u^{(i)}}{B_U N_0}), \tag{44}$$

is linear on $s_U^{(i)}$. Then, the achievable data rate of SU i in (12) can be rewriteen as

$$R_i = -f(c_L^{(i)}, \frac{p_L^{(i)} h_L^{(i)}}{N_0}) + s_U^{(i)} \log(1 + \frac{p_U^{(i)} h_U^{(i)}}{B_U N_0}). \tag{45}$$

Since the summation of concave and linear functions is also a concave function, (19) is a convex optimization problem.

APPENDIX D
PROOF OF THEOREM 1

The Lagrangian function for problem (19) is written as

$$\begin{aligned} L(&\mathbf{c}_L, \mathbf{s}_U, \mathbf{p}_L, \lambda, \beta, \mu) \\ &= \sum_{i \in \mathcal{U}} s_U^{(i)} + \sum_{i \in \mathcal{U}} \lambda_i (r_i - R_i) \\ &\quad + \beta(\sum_{i \in \mathcal{U}} c_L^{(i)} - C_L) + \mu(\sum_{i \in \mathcal{U}} p_L^{(i)} - P), \end{aligned} \tag{46}$$

where $\mathbf{c}_L = (c_L^{(i)})_{i \in \mathcal{U}}$, $\mathbf{s}_U = (s_U^{(i)})_{i \in \mathcal{U}}$, $\mathbf{p}_L = (p_L^{(i)})_{i \in \mathcal{U}}$, λ, β, and μ are the Lagrangian multipliers related to the constraints (19a), (19b), and (19c), respectively. Then based on the KKT conditions, the following conditions must be satisfied with the optimal solution

$$\frac{\partial L}{\partial c_L^{(i)}} = 0, \quad i \in \mathcal{U}, \tag{47}$$

$$\frac{\partial L}{\partial s_U^{(i)}} = 0, \quad i \in \mathcal{U}, \tag{48}$$

$$\frac{\partial L}{\partial p_L^{(i)}} = 0, \quad i \in \mathcal{U}, \tag{49}$$

$$\lambda_i (r_i - R_i) = 0, \quad i \in \mathcal{U}, \tag{50}$$

$$\beta(\sum_{i \in \mathcal{U}} c_L^{(i)} - C_L) = 0, \tag{51}$$

$$\mu(\sum_{i \in \mathcal{U}} p_L^{(i)} - P) = 0. \tag{52}$$

Based on (48), we can derive

$$\lambda_i = \frac{1}{\log\left(1 + \frac{p_U^{(i)} h_U^{(i)}}{B_U N_0}\right)}, \quad \forall i \in \mathcal{U}. \tag{53}$$

Then according to (50), we have $R_i = r_i$, $\forall i \in \mathcal{U}$. Based on (47), we can derive

$$\frac{p_L^{(i)} h_L^{(i)}}{p_L^{(i)} h_L^{(i)} + c_L^{(i)} N_0} = \log\left(1 + \frac{p_L^{(i)} h_L^{(i)}}{c_L^{(i)} N_0}\right) - \frac{\beta}{\lambda_i}. \tag{54}$$

If the licensed bandwidth is enough to satisfy the data rate requirements of SUs, then we have

$$\log\left(1 + \frac{p_L^{(i)} h_L^{(i)}}{c_L^{(i)} N_0}\right) = \frac{r_i}{c_L^{(i)}}, \quad \forall i \in \mathcal{U}. \tag{55}$$

Substituting (55) into (54), we have condition (20). Furthermore, with (49), we have the condition (21),

$$p_L^{(i)} = c_L^{(i)} \left(\frac{\lambda_i}{\mu} - \frac{N_0}{h_L^{(i)}}\right). \tag{56}$$

By formulating simultaneous equations (51), (52), (53), (20), and (21), we can judge whether the available licensed bandwidth in the SBS is enough or not. If there is a solution for these equations, then the available licensed bandwidth is enough to satisfy the QoS of SUs. Otherwise, the unlicensed band utilization is required.

Appendix E
Proof of Existence of a Unique Solution

We need to calculate the collision probability, p_F, experienced by the Wi-Fi users according to nonlinear equations (1), (3) and (16) after finding the amount of unlicensed bandwidth, S_U, required by the SBS. Here, we rewrite the equations (1), (3), and (16) as followings

$$\tau = \frac{2 \times (1 - 2p_F)}{(1 - 2p_F)(W_F + 1) + p_F W_F (1 - (2p_F)^{m_F})}, \quad (57)$$

$$p_F = 1 - (1 - \eta_B)(1 - \tau)^{n-1}, \quad (58)$$

$$S_U = \eta_B (1 - \tau)^n. \quad (59)$$

Herein, we ignore the index k for Wi-Fi AP k in (57) and (58) since the calculation process is same for each Wi-Fi AP when the SBS shares unlicensed channels with multiple Wi-Fi APs. After finding out the value of S_U in step 8, based on (59), η_B is given by

$$\eta_B = S_U (1 - \tau)^{-n}. \quad (60)$$

Substituting (60) back onto (58), we have

$$p_F = 1 - (1 - \tau)^{n-1} + S_U (1 - \tau)^{-1}. \quad (61)$$

Combine (61) and (57), we have a nonlinear system with two unknown variables τ and p_F since W_F and m_F are constants. In the following, we prove that there has a unique solution for this system.

Taking derivative of (61) with respect to p_F, we have

$$\frac{\partial \tau}{\partial p_F} = \frac{1}{(n - 1)(1 - \tau)^{n-2} + S_U (1 - \tau)^{-2}}. \quad (62)$$

Since n is equal or larger than one, $p_F \in [0, 1]$ and $\tau \in [0, 1]$, (62) is always greater than zero. Therefore, τ is monotonically increasing with respect to p_F in (61). Moreover, base on (58), we have

$$\tau = 1 - \left(\frac{1 - p_F}{1 - \eta_B}\right)^{\frac{1}{n-1}}, \quad (63)$$

where $0 \le \tau \le 1$. Then, according to (63), with any η_B, when $p_F = 0$, the minimum value of τ is zero. When $p_F = 1$, the maximum value of τ is one. Therefore, the value of τ increases from 0 to 1 with respect to p_F in (61).

On the other hand, (57) can be rewritten as

$$\tau = \frac{2}{W_F + 1 + p_F W_F \sum_{i=0}^{m_F - 1} (2p_F)^i}. \quad (64)$$

Then, taking derivative of (64) with respect to p_F, we have

$$\frac{\partial \tau}{\partial p_F} = \frac{-\left(2W_F \sum_{i=0}^{m_F-1} (2p_F)^i + p_F W_F \sum_{i=0}^{m_F-1} i \cdot (2p_F)^{i-1}\right)}{\left(W_F + 1 + p_F W_F \sum_{i=0}^{m_F-1} (2p_F)^i\right)^2}, \quad (65)$$

which is less than zero. Therefore, (58) is a monotonically decreasing function with respect p_F. Since $p_F \in [0, 1]$, τ decreases from $2/(1 + 2^m W_F)$ to $2/(W_F + 1)$. On the other hand, as we described above, τ increases from 0 to 1 with respect to p_F and $2/(1 + 2^m W_F) > 0$ and $2/(W_F + 1) < 1$. Therefore, we know there is a unique solution for the nonlinear system.

References

[1] *Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2014–2019*, San Jose, CA, USA, Cisco, Feb. 2015.

[2] *Release 13-3GPP*, accessed on Oct. 2015. [Online]. Available: http://www.3gpp.org/release-13

[3] M. I. Rahman, A. Behravan, H. Koorapaty, J. Sachs, and K. Balachandran, "License-exempt LTE systems for secondary spectrum usage: Scenarios and first assessment," in *Proc. IEEE Symp. DySPAN*, Aachen, Germany, May 2011, pp. 349–358.

[4] T. Nihtilä *et al.*, "System performance of LTE and IEEE 802.11 coexisting on a shared frequency band," in *Proc. IEEE WCNC*, Shanghai, China, Apr. 2013, pp. 1038–1043.

[5] E. Perahia and R. Stacey, *Next Generation Wireless LANs: 802.11n and 802.11ac*. Cambridge, U.K.: Cambridge Univ. Press, 2013.

[6] F. M. Abinader *et al.*, "Enabling the coexistence of LTE and Wi-Fi in unlicensed bands," *IEEE Commun. Mag.*, vol. 52, no. 11, pp. 54–61, Nov. 2014.

[7] "LTE in unlicensed spectrum: Harmonious unlicensed spectrum," Qualcomm, San Diego, CA, USA, White Paper, Jun. 2014.

[8] F. Liu, E. Bala, E. Erkip, and R. Yang, "A framework for femtocells to access both licensed and unlicensed bands," in *Proc. WiOpt*, Princeton, NJ, USA, May 2011, pp. 407–411.

[9] F. Liu, E. Erkip, M. C. Beluri, R. Yang, and E. Bala, "Dual-band femtocell traffic balancing over licensed and unlicensed bands," in *Proc. IEEE ICC*, Ottawa, ON, Canada, Jun. 2012, pp. 6809–6814.

[10] R. Ratasuk *et al.*, "License-exempt LTE deployment in heterogeneous network," in *Proc. ISWCS*, Paris, France, Aug. 2012, pp. 246–250.

[11] "LTE for unlicensed spectrum," Nokia, Espoo, Finland, White Paper, 2014.

[12] "U-LTE: Unlicensed spectrum utilization of LTE," Huawei, Shenzhen, China, White Paper, 2014.

[13] "Broadband radio access networks (BRAN); 5 GHz high performance RLAN; harmonized EN covering the essential requirements of article 3.2 of the R&TTE directive," Eur. Telecommun. Standards Inst., Sophia Antipolis, France, Tech. Rep. EN 301 893 v1.7.1, Jun. 2012.

[14] A. Babaei, J. Padden, and J. Andreoli-Fang, *Overview of EU LBT and Its Effectiveness for Coexistence of LAA LTE and Wi-Fi*, document IEEE 802.19-14/0082r0, Nov. 2014.

[15] A. T. Gamage and X. S. Shen, "Uplink resource allocation for interworking of WLAN and OFDMA-based femtocell systems," in *Proc. IEEE ICC*, Budapest, Hungary, Jun. 2013, pp. 6071–6075.

[16] M. Ismail and W. Zhuang, "A distributed multi-service resource allocation algorithm in heterogeneous wireless access medium," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 2, pp. 425–432, Feb. 2012.

[17] A. R. Elsherif, W.-P. Chen, A. Ito, and Z. Ding, "Adaptive small cell access of licensed and unlicensed bands," in *Proc. IEEE ICC*, Budapest, Hungary, Jun. 2013, pp. 6327–6332.

[18] A. Bhorkar, C. Ibars, and P. Zong, "Performance analysis of LTE and Wi-Fi in unlicensed band using stochastic geometry," in *Proc. IEEE PIMRC*, Washington, DC, USA, Sep. 2014, pp. 1310–1314.

[19] A. Babaei, J. Andreoli-Fang, and B. Hamzeh, "On the impact of LTE-U on Wi-Fi performance," in *Proc. IEEE PIMRC*, Washington, DC, USA, Sep. 2014, pp. 1621–1625.

[20] S. Hajmohammad and H. Elbiaze, "Unlicensed spectrum splitting between femtocell and WiFi," in *Proc. IEEE ICC*, Budapest, Hungary, Jun. 2013, pp. 1883–1888.

[21] F. Liu, E. Bala, E. Erkip, M. C. Beluri, and R. Yang, "Small-cell traffic balancing over licensed and unlicensed bands," *IEEE Trans. Veh. Technol.*, vol. 64, no. 12, pp. 5850–5865, Dec. 2015.

[22] F. Teng, D. Guo, and M. L. Honig, "Sharing of unlicensed spectrum by strategic operators," in *Proc. IEEE GlobalSIP*, Atlanta, GA, USA, Dec. 2014, pp. 288–292.

[23] R. Yin, G. Yu, A. Maaref, and G. Y. Li, "Adaptive LBT for licensed assisted access LTE networks," in *Proc. IEEE GLOBECOM*, San Diego, CA, USA, Dec. 2015, pp. 1–6.

[24] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 3, pp. 535–547, Mar. 2000.

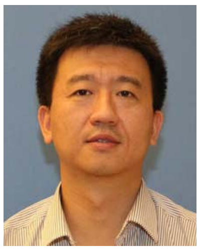
[25] D. Malone, K. Duffy, and D. Leith, "Modeling the 802.11 distributed coordination function in nonsaturated heterogeneous conditions," *IEEE/ACM Trans. Netw.*, vol. 15, no. 1, pp. 159–172, Feb. 2007.

[26] J. Spall, "Stochastic optimization," in *Handbook of Computational Statistics*. Springer, 2004.

[27] "The mobile broadband spectrum challenge: International comparisons," Federal Commun. Commission, Washington, DC, USA, White Paper, Feb. 2013.

[28] G. Bianchi and I. Tinnirello, "Kalman filter estimation of the number of competing terminals in an IEEE 802.11 network," in *Proc. IEEE INFOCOM*, vol. 2. San Francisco, CA, USA, Mar. 2003, pp. 844–852.

[29] A. L. Toledo, T. Vercauteren, and X. Wang, "Adaptive optimization of IEEE 802.11 DCF based on Bayesian estimation of the number of competing terminals," *IEEE Trans. Mobile Comput.*, vol. 5, no. 9, pp. 1283–1296, Sep. 2006.



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