Harmonious Coexistence and Efficient Spectrum Sharing for LTE–U and Wi–Fi

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***Abstract*—Extending LTE to unlicensed bands (LTE-U) is gaining increasing interest recently. However, its success faces great challenges due to the inherent lack of compatibility between LTE and Wi-Fi. In this paper, we address the problem of harmonious coexistence and efficient spectrum sharing for LTE-U and Wi-Fi. We develop an analysis framework for the Carrier Sensing Adaptive Transmission (CSAT) mechanism, which leads to a Listen-Before-Talk (LBT) enhanced CSAT scheme that achieves capacity gains for both LTE-U and Wi-Fi, and provides useful guidelines on achieving fairness. For efficient spectrum sharing among LTE-U Pico Evolved NodeBs (PeNBs), we propose an Inter-Cell Interference Coordination (ICIC) based spectrum share mechanism incorporated into a spectrum auction framework. Both the analysis and the superior performance of the proposed scheme are validated with simulations and comparison with several benchmarks.**

***Keywords*-LTE-U; LTE LAA; Wi-Fi; CSAT; Listen-before-Talk; cross-technology coexistence; Auction.**

I. Introduction

As a promising technology to meet the so–called 1000x mobile data challenge, extending LTE to unlicensed bands has recently gained significant attention [1], [2]. To this end, three major technologies have been proposed, (i) LTE–U that is based on 3GPP Release 10/11/12 and adopted in the USA, Korea, India, etc., (ii) Licensed–Assisted Access (LAA) that is based on 3GPP Release 13 and adopted in the Europe, Japan, etc., and (iii) MuLTEfire that solely operates in the unlicensed spectrum. These technologies can exploit the unlicensed bands (i.e., the 5GHz Unlicensed National Information Infrastructure (U–NII) spectrum) with or without licensed bands to achieve high data rates for enhanced user experience [3].

Despite many appealing benefits, extending LTE to unli–censed bands is still far from wide deployment. LTE adopts a centralized radio resource management scheme that is incom–patible with that of current unlicensed band users, i.e., Wi–Fi devices, which adopt CSMA/CA for multi–user sharing of the channel. If applying LTE in unlicensed bands without any careful modification for coexistence, it would severely degrade the performance of Wi–Fi devices [4]. Such degradation would be unacceptable to Wi–Fi users.

Hence, harmonious coexistence of LTE–U and Wi–Fi is critical to the success of this new wireless networking paradigm [6]. To this end, *Carrier-Sensing Adaptive Transmission* (CSAT) (in LTE–U) and *Listen Before Talk* (LBT) (in LAA) have been proposed to address the coexistence problem. CSAT is a duty cycling approach that defines a time frame structure. LTE Pico Evolved NodeBs (PeNB) transmit in a fraction of the time frame and gate off in the remaining portion. In other words, CSAT allows Wi–Fi to utilize a portion of the time frame and the length of such portion of time can be adaptively adjusted according to Wi–Fi activities. LBT is a simplified version of 802.11 Distributed Coordination Function (DCF). It requires LTE equipment to periodically sense the presence of other devices in the channel before transmission, and can thus avoid collision with Wi–Fi. However, neither CSAT nor LBT is the ultimate solution for coexistence between LTE and Wi–Fi. With CSAT, there are still considerable unavoidable collisions with Wi–Fi, which will be discussed in detail in Section IV. LBT alone would make it hard to coordinate multiple LAA PeNBs, due to the lack of time synchronization [5].

In this paper, we present a systematic approach to harmo–nious coexistence of LTE–U and Wi–Fi in unlicensed bands. We not only address the problem with a rigorous analytical framework, but also develop an effective scheme based on a theoretic model to enable efficient spectrum sharing among LTE–U PeNBs. In particular, we first address the LTE–U and Wi–Fi coexistence problem with an *LBT enhanced CSAT* scheme. Through analysis and simulations, we show that the proposed scheme can achieve significantly improved capacity over CSAT for both LTE–U and Wi–Fi, and derive useful guide–lines on CSAT configuration for guaranteed fairness to Wi–Fi stations. We then address the problem of efficient spectrum sharing among LTE–U PeNBs with an auction based scheme that incorporates ICIC for center and edge User equipments (UE). The analysis and the performance of the proposed schemes are validated with simulations, as well as comparison with several benchmark schemes, where considerable capacity gains and guaranteed fairness are observed.

In the remainder of this paper, we discuss related work in Section II and the system model in Section III. We present the analysis of CSAT and LBT enhanced CSAT in Section IV, and the proposed spectrum sharing for LTE–U PeNBs in Section V. Simulation results are discussed in Section VI and Section VII concludes this paper.

II. Related Work

Motivated by the considerable amount of underutilized spectrum, extending the well designed OFDMA based LTE into unlicensed bands attracts great interest in recent years. Through extensive field tests [7] and simulation studies [4],

2155-6814/17 $31.00 © 2017 IEEE
DOI 10.1109/MASS.2017.69

[8], it has been shown that applying LTE in unlicensed bands without considerable modification of LTE for coexistence, would cause significant performance degradation to Wi-Fi, while the performance of LTE would just be slightly affected. This is because that CSMA/CA based Wi-Fi network would suffer long backoffs when the channel is occupied by the LTE.

To ensure harmonious coexistence of LTE and Wi-Fi, CSAT and LBT were introduced and considered as two promising technical solutions for LTE/Wi-Fi coexistence. Simulation studies [8], [9] and analysis [9], [10] showed that CSAT could limit the impact of LTE on Wi-Fi, if parameters of *LTE ON* and *LTE OFF* phases were properly selected in response to Wi-Fi activities on the channel [1], [9], [10]. LBT is required by regulations in Europe, Japan, and India. It requires LTE to listen to the channel before transmission, and transmit only when the channel is not occupied by others devices. Simulations showed that LBT reduces the impact of LTE on Wi-Fi [11]–[15]. However, it has also been shown that Wi-Fi may still be pushed back by LTE even when LBT was applied. Hence several works have been conducted to model the performance of the LBT [11] and several adaptive LBT mechanisms have been proposed recently [12]–[15]. In [16], the authors develop a technique to decode overlapping LTE and Wi-Fi transmissions, which, however, requires to redesign the PHY of both LTE and Wi-Fi. In [17], a cognitive coexistence scheme is proposed to jointly determine dynamic channel selection, carrier aggregation and fractional spectrum access for unlicensed LTE networks (U-LTE), where fairness is guaranteed by solving a mixed integer nonlinear optimization problem with branch and bound and convex relaxation.

Another challenge to the success of LTE-U is the coexistence among LTE-U PeNBs [6], [18]–[20]. Various techniques have been proposed to address this issue, such as a channel selection algorithm based on a time domain inter-cell coordination solution [18], Q-learning [19], and a Laypunov optimization based auction mechanism [6]. A spectrum sharing strategy was proposed in [20], in which the PeNBs scan and assign for available spectrum for UEs.

III. Problem Statement and System Model

In this paper, we consider the coexistence scenario of multiple LTE PeNBs from the same or different operators, as well as multiple Wi-Fi stations co-located in the 5GHz unlicensed band. The goal is to provide a rigorous analytical framework and coexistence strategy to enable (i) harmonious coexistence of LTE-U and Wi-Fi in unlicensed band, and (ii) efficient sharing of unlicensed spectrum among LTE-PeNBs.

Specifically, consider a system with a set of LTE PeNBs, denoted as $\mathcal{M}$. Each PeNB i, $i \in \mathcal{M}$, serves a set of UEs, denoted as $\mathcal{L}_i$. There are also a set of Wi-Fi stations co-located with the LTE PeNBs, denoted by $\mathcal{N}$. The LTE PeNBs and Wi-Fi stations share a set $\mathcal{H}$ of unlicensed channels. The spectrum of a channel can be further divided into a set $\mathcal{K}$ of sub-channels, with Orthogonal frequency-division multiplexing (OFDM). The bandwidth of a sub-channel corresponds to that of a resource block (RB) in LTE (e.g., multiple subcarriers).

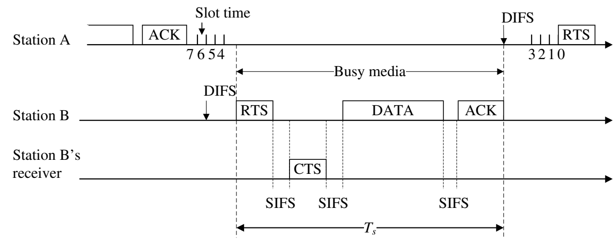

Fig. 1. An illustration of 802.11 DCF with the RTS/CTS mechanism.

We assume that all LTE users are covered by the LTE Macrocell eNodeB. The licensed bands support all control information as well as both uplink and downlink data transmissions, while the unlicensed bands provide extra data transmissions for the downlink [3] (i.e., as in LAA). The LTE-PeNBs are connected to the LTE Macrocell eNodeB with a high-speed backbone, and they can also communicate with each other through the X2 interface, which is necessary for coordinating the operation of the PeNBs.

IV. Harmonious Coexistence of Wi-Fi and LTE-U

In this section, we address the *first problem* of enabling harmonious coexistence of Wi-Fi and LTE-U. Although LBT has been shown effective for coexistence with Wi-Fi [5], [6], [13], we consider the duty-cycling approach, i.e., CSAT [1], in this paper, since it requires minimal changes to the LTE air interface [3]. We develop an analysis for CSAT and Wi-Fi capacity, which leads to an LBT Enhanced CSAT scheme that can achieve higher capacity for both Wi-Fi and LTE-U. The analysis also provides useful guidelines on how to set LTE-U parameters to achieve fairness between the two technologies.

A. Distributed Coordination Function of 802.11

We assume that all Wi-Fi stations adopt DCF, i.e., the RTS/CTS mechanism for channel access, as shown in Fig. 1. It takes T_s to successfully transmit a data frame. Specifically, each station senses the channel when it has a frame to send. If the channel is detected as idle for a period of Distributed InterFrame Space (DIFS), denoted as T_d, the station transmits the frame. Otherwise it keeps on sensing the channel until the channel is detected idle for a DIFS interval. In this case, the station backs off for a random period of time before transmission. The backoff time is slotted (with a slot time σ). DCF also adopts the exponential backoff mechanism. The backoff time is randomly selected in $(0, W_{max})$, while $W_{max} = 2^m W_{min}$ after m collisions.

With the RTS/CTS mechanism, the hidden terminal problem can be solved. Stations rely on acknowledgment (ACK) to detect collisions. After a successful reception, the receiving station returns an ACK right after a Short InterFrame Space (SIFS). As the SIFS is shorter than DIFS plus the propagation delay, ACKs do not collide with other transmissions. If ACK is not received within a time period of ACK_Timeout or the transmission of a different frame is detected, a collision is assumed to have occurred and the station reschedules the transmission according to the backoff rules.

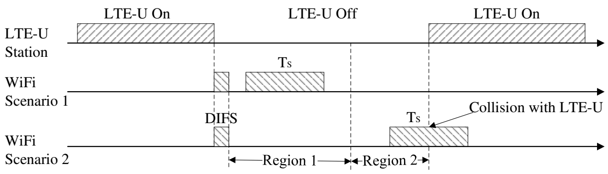

Fig. 2. An illustration of CSAT and its coexistence with Wi–Fi.

B. CSAT Capacity Analysis

CSAT is a duty–cycling approach. It defines a time frame structure of duration T_{cyc}, during which LTE–U is turned on in a fraction of the frame (with duration T_{on}), and off in the remaining fraction (with duration T_{off}). The *LTE-U ON* and *LTE-U OFF* durations can be adjusted according to sensed medium activities of Wi–Fi stations. CSAT and its coexistence with Wi–Fi are illustrated in Fig. 2.

When LTE–U is on, Wi–Fi stations will sense a busy channel and will not attempt any transmissions. When LTE–U is off, Wi–Fi stations can access the channel as in Section IV–A. A Wi–Fi station may collide with LTE–U or other Wi–Fi stations. Specifically, the LTE–U OFF period can be divided in to *Region 1* and *Region 2*. The duration of Region 2, denoted as T_s, is the time required for a Wi–Fi station to complete a transmission (see Fig. 1). We assume a T_s value corresponding to the maximum payload size for Wi–Fi (i.e., with the saturate throughput assumption [21]). If a Wi–Fi station initiates a transmission in Region 1, it may collide with other Wi–Fi stations, but not with LTE–U. If a Wi–Fi station initiates a transmission in Region 2, a collision is ensured: the Wi–Fi transmission will collide with LTE–U as well as other possible Wi–Fi transmissions. The probability of collision when a frame is initiated, i.e., the conditional collision probability, denoted by p, can be written as

$$p = \frac{T_s}{T_{off} - T_d} + (1 - (1-\tau)^{(n-1)}) \frac{T_{off} - T_d - T_s}{T_{off} - T_d}, \quad (1)$$

where n is the number of Wi–Fi stations and τ is the Wi–Fi transmission probability when the channel is sensed idle.

For Wi–Fi stations, τ is only related to p and the back–off strategy. Therefore, the two–dimensional Markov chain model in [21] is still applicable to this coexistence scenario. From [21], the transmission probability τ can be derived as

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1) + pW(1-(2p)^m)}, \quad (2)$$

where m is the largest backoff stage beyond which W will not be increased [21]. Let P_{tr} be the probability that at least one station transmits in a random slot in the LTE–U OFF phase. Then we have

$$P_{tr} = 1 - (1-\tau)^n, \quad (3)$$

since a successful transmission occurs when exactly one station transmits in Region 1. The conditional probability that a Wi–Fi transmission is successful, P_s, can be written as

$$P_s = \frac{T_{off} - T_d - T_s}{T_{off} - T_d} \cdot \frac{n\tau(1-\tau)^{n-1}}{P_{tr}}, \quad (4)$$

where $\frac{T_{off} - T_d - T_s}{T_{off} - T_d}$ is the probability that a transmission is initiated in Region 1, as the transmission start time is evenly distributed in the T_{off} phase after a DIFS followed by the previous LTE–U ON phase.

We can numerically solve (1) and (2) for p and τ. The throughput of Wi–Fi can be derived as in [21].

$$S_{WiFi} = \frac{\mathbb{E}\{\text{amount of data transmitted in a slot time}\}}{\mathbb{E}\{\text{length of a slot time}\}}. \quad (5)$$

Let $\mathbb{E}\{P\}$ be the expected data size in a successful Wi–Fi transmission, the throughput of all Wi–Fi stations can be derived as

$$S_{WiFi} = \frac{T_{off} - T_d}{T_{off} + T_{on}} \times \quad (6)$$
$$\frac{P_s P_{tr} \mathbb{E}[P]}{(1-P_{tr})\sigma + P_{tr}P_s(T_s + T_d) + P_{tr}(1-P_s)\mathbb{E}\{T_c^*\}}.$$

In (6), $\mathbb{E}\{T_c^*\}$ is the expected time a collision transmission spends in the T_{off} phase, which can be derived as

$$\mathbb{E}\{T_c^*\} = P(\text{with LTE–U only}|\text{collision}) \times \int_0^{T_s} \frac{T_s - t}{T_s} dt +$$
$$P(\text{with Wi–Fi only}|\text{collision}) \times T_c +$$
$$P(\text{with both LTE–U \& Wi–Fi}|\text{collision}) \times \int_0^{T_c} \frac{T_c - t}{T_c} dt,$$

where $\int_0^{T_s} \frac{T_s - t}{T_s} dt$ is the expectation of the time a collision transmission spends in the T_{off} phase when colliding with LTE–U; T_c is the time spent on the collision with Wi–Fi stations; and $\int_0^{T_c} \frac{T_c - t}{T_c} dt$ is the expected time a collision transmission spends in the T_{off} phase when colliding with both Wi–Fi and LTE–U stations. Then we have

$$\mathbb{E}\{T_c^*\} = \frac{1}{P_{tr}(1-P_s)} \frac{T_s}{T_{off} - T_d} n\tau(1-\tau)^{n-1} \cdot \frac{T_s}{2} + \quad (7)$$
$$\frac{1}{P_{tr}(1-P_s)} \frac{T_{off} - T_d - T_c}{T_{off} - T_d} \cdot (P_{tr} - n\tau(1-\tau)^{n-1})T_c +$$
$$\frac{1}{P_{tr}(1-P_s)} \frac{T_c}{T_{off} - T_d} \cdot (P_{tr} - n\tau(1-\tau)^{n-1}) \frac{T_c}{2}.$$

The first several frames of LTE–U in the T_{on} phase may collide with Wi–Fi transmissions. If a Wi–Fi station collides with LTE–U, the Wi–Fi station has no way to detect the colli–sion and the interference will continue until the transmission is over. If we ignore the resource blocks that only part of their time slot is interfered by Wi–Fi, the normalized throughput of LTE–U, defined as the fraction of time the channel is used to transmit data without interference, can be derived as follows.

$$S_{LTE-U} \leq \frac{T_{on} - \mathbb{E}\{T_I^*\}}{T_{on} + T_{off}}, \quad (8)$$

where $\mathbb{E}\{T_I^*\}$ is the expected time period in the LTE–U ON phase interfered by Wi–Fi. Let P_d be the probability that LTE–U collides with a Wi–Fi frame. It follows that

$$\mathbb{E}\{T_I^*\} \geq P_d \times \int_0^{T_s} \frac{T_{data} - t}{T_{data}} dt, \quad (9)$$

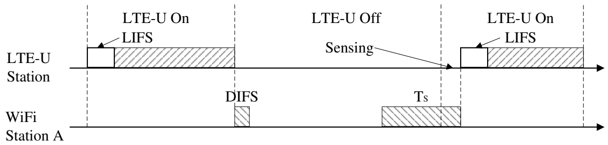

Fig. 3. An illustration of LBT enhanced CSAT.

where T_{data} is the time length of a Wi–Fi frame and the integral is the expected time that a Wi–Fi data frame interferes with LTE–U. The probability that LTE–U interferes with a Wi–Fi frame is the probability that a Wi–Fi station transmits when the LTE–U ON phase starts. If we assume that the activities of Wi–Fi stations in the LTE–U ON phase are stationary, then P_d can be derived as

$$P_d = \frac{P_s^* P_{tr} T_{data}}{(1-P_{tr}\sigma) + P_{tr}P_s^*(T_s+T_d) + P_{tr}(1-P_s^*)T_c},$$

where $P_s^* = n\tau(1-\tau)^{n-1}/P_{tr}$ is the conditional probability that there is no collision among Wi–Fi stations.

C. LBT Enhanced CSAT

In the proposed LBT Enhanced CSAT scheme, an LTE–U PeNB is required to immediately sense the channel after entering the LTE–U ON phase. If the channel has been sensed idle for an LIFS interval, which is longer than the propagation delay plus SIFS, but shorter than DIFS, then the LTE–U PeNB starts to transmit in the next LTE frame, and keeps on transmitting until the end of the LTE–U ON phase. When the channel is idle at the beginning of the LTE–U ON phase, using the shorter LIFS can greatly reduce the chance of collision with Wi–Fi transmissions. When the channel is busy at the beginning of the LTE–U ON phase, LTE–U will wait until the current Wi–Fi transmission is over, continue to wait for an LIFS, and then start transmission. Again, the shorter LIFS can ensure LTE–U wins the channel when it becomes idle.

The proposed scheme is illustrated in Fig. 3. The goal is to avoid collision between LTE–U and Wi–Fi in the beginning of the LTE–U ON phase. The decreased collision rate brings about at least two advantages, i.e., (i) less idle time slots spent in the backoff stage and (ii) less time slots wasted in collision. Philosophically the proposed scheme is like LBT, but it only senses the channel in the beginning of each LTE–U ON phase (rather than for each LTE–U transmission frame). Obviously the proposed approach is more efficient. The duty–cycle of the CSAT can be easily adjusted for different traffic conditions to ensure fair spectrum sharing with Wi–Fi.

As most collisions between LTE–U and Wi–Fi can be avoided by LBT, the Wi–Fi transmission rate τ and the conditional collision probability p can be computed as in [21]. We still have $P_{tr} = 1-(1-\tau)^n$, and the probability that a successful transmission occurs conditioned on at least one transmission is made in that random slot, P_s, can be derived as

$$P_s = n\tau(1-\tau)^{n-1}/P_{tr}. \tag{10}$$

The throughput of all Wi–Fi stations can be written as

$$S_{WiFi} = \frac{T_{off} - T_d + \mathbb{E}[T_b^*]}{T_{on}+T_{off}} \times \frac{P_s P_{tr}\mathbb{E}[P]}{(1-P_{tr}\sigma) + P_{tr}P_s(T_s+T_d) + P_{tr}(1-P_s)T_c}, \tag{11}$$

where $\mathbb{E}[T_b^*]$ is the expected time duration that Wi–Fi stations backoff as caused by LTE–U. Assume that the Wi–Fi activities observed at the start of LTE–U ON phase, denoted as t_{start}, are stationary. The probability of the channel state at t_{start} is the probability of the channel state observed at a random time. Under this assumption, we have

$$\mathbb{E}\{T_b^*\} = T_{LIFS} + P(\text{Wi–Fi collision at } t_{start}) \times \frac{T_c}{2} + P(\text{Wi–Fi transmission successful at } t_{start}) \times \frac{T_s}{2}.$$

The probability that the channel experiences collision at t_{start} is $\frac{P_{tr}P_sT_s}{(1-P_{tr}\sigma)+P_{tr}P_sT_s+P_{tr}(1-P_s)T_c}$. The probability that the channel is under a successful transmission at t_{start} can be derived as $\frac{P_{tr}(1-P_s)T_c}{(1-P_{tr}\sigma)+P_{tr}P_sT_s+P_{tr}(1-P_s)T_c}$. If we further neglect the LIFS interval, it follows that

$$\mathbb{E}[T_b^*] = T_{LIFS} + \frac{P_{tr}P_sT_sT_s/2 + P_{tr}(1-P_s)T_cT_c/2}{(1-P_{tr})\sigma + P_{tr}P_sT_s + P_{tr}(1-P_s)T_c}. \tag{12}$$

For LTE–U stations, the normalized capacity can then be derived as follows.

$$S_{LTE-U} = \max\left\{\frac{T_{on} - \mathbb{E}\{T_b^*\}}{T_{off}+T_{on}}, 0\right\}. \tag{13}$$

D. Fair Coexistence of LTE-U and Wi-Fi

For the success of LTE–U, it is critical to ensure a fair coexistence with Wi–Fi. A reasonable fairness criterion is that *when introducing an LTE-U PeNBs into the unlicensed band, the impact to the existing Wi-Fi stations should be no more than that of adding a Wi-Fi station* [2], [17].

With the capacity analysis of Wi–Fi and LTE–U coexistence, we are now ready to enforce the above fairness criterion. The number of Wi–Fi stations can be estimated according to [5]. Assume that there are n Wi–Fi stations on the channel, the following inequality should be satisfied to ensure fairness.

$$S_{WiFi}(n)/n \geq S(n+1)/(n+1), \tag{14}$$

where $\frac{S_{WiFi}(n)}{n}$ is the normalized Wi–Fi capacity with n Wi–Fi stations and LTE–U, which can be computed using (6) or (11). $\frac{S(n+1)}{n+1}$ is the normalized capacity of an $(n+1)$–node Wi–Fi network without LTE–U, which can be computed as in [21].

Then, we can tune the LTE–U ON/OFF periods, T_{on} and T_{off}, to maximize the normalized throughput of LTE–U, while ensuring fairness to Wi–Fi stations by satisfying (14). The duty cycle of CSAT or LBT enhanced CSAT is achieved by muting some of the subframes of LTE–U PeNBs [3]. Hence, the length of LTE–U ON and LTE–U OFF phases should be multiples of subframe length, which is 1 ms.

Although there is no closed–form solutions for $S_{WiFi}(n)$ and $S(n+1)$, we show an easy way to solve the problem.

Observe that the normalized Wi–Fi throughput increases *monotonically* with T_{off} (also validated in our simulations). Hence, for a given T_{cyc}, we can search for a T^*_{off} such that

$$\begin{cases} \frac{S_{WiFi}(n,T^*_{off}|T_{cyc})}{n} \geq \frac{S(n+1)}{n+1} \\ \frac{S_{WiFi}(n,T^*_{off}-1|T_{cyc})}{n} < \frac{S(n+1)}{n+1}, \end{cases} T^*_{off} \in \{0,...,T_{cyc}\}, \quad (15)$$

where $S_{WiFi}(T_{off}|T_{cyc})$ is the Wi–Fi capacity with CSAT or LBT enhanced CSAT, as a function of T_{off} for a given T_{cyc}.

V. Efficient Spectrum Sharing for LTE–U

Once fair and efficient coexistence of LTE–U and Wi–Fi is achieved, we now focus on efficient spectrum sharing among LTE–U PeNBs, to coordinate their access to the unlicensed spectrum during the LTE–U ON phase. Unlike macrocells, the PeNB deployment may not be well planned, especially when they belong to different operators. Interference management is thus the key to the spectrum sharing problem.

Inter–cell interference coordination (ICIC) is introduced in 3GPP release 8 to deal with interference at cell edge for LTE. In this section, we allow each PeNBs to utilize all resource blocks. However, to avoid difficulties of time synchronization among neighboring PeNBs, especially for PeNBs from different operators, no two neighboring PeNBs should use the same spectrum for cell edge users at the same time. Thus the success of ICIC relies on spectrum assignment among PeNBs for cell–edge users. For LTE in licensed bands, all eNBs/PeNBs are with the same operator and centralized spectrum assignment can be used. For LTE–U, neighboring PeNBs from the same or different operators may operate on the same channel, which calls for distributed approaches for spectrum assignment among PeNBs for cell–edge users.

A. Utility and Social Welfare

We propose a fair and efficient spectrum assignment scheme based on game theory in this section. We first define the *neighbor matrix* of PeNBs. Two PeNBs are considered to be neighbors if the mutual interference is non–negligible. The neighbor matrix is defined as follows.

$$I_{i,j} = \begin{cases} 1, & \text{if BS } i \text{ and } j \text{ are neighbors} \\ 0, & \text{otherwise.} \end{cases} \quad (16)$$

To minimize the co–channel interference among PeNBs, neighboring PeNBs should not use a certain spectrum for cell edge UEs unless successfully bidding for it. With the proposed scheme, each PeNB i can utilize all the spectrum, denoted by B, in the LTE–U ON phase to serve its UE set $\mathcal{L}_i$. The spectrum can be used *for free* to serve its cell center UEs (denoted as $\mathcal{L}^C_i$), with total amount $0 \leq B^C_i \leq B$. The PeNB can also bid for spectrum to serve its edge users (denoted as $\mathcal{L}^E_i$), with spectrum $B^E_i = B - B^C_i$ and a payment of $\tilde{p}_i$.

We consider homogeneous property among different spec– trum, so the utility of a PeNB only depends on the amount of spectrum for cell edge users and the coexistence strategy of LTE–U PeNBs. The utility of PeNB i, $i \in \mathcal{M}$, is defined as

$$U_i(B^E_i) = \max\left\{\sum_{j\in\mathcal{L}^E_i}\log(r(b_j)) + \sum_{j\in\mathcal{L}^C_i}\log(r(b_j))\right\} - \max\left\{\sum_{j\in\mathcal{L}_i|B^E_i=0}\log(r(b_j))\right\} - \tilde{p}_i, \quad (17)$$

where b_j is the spectrum allocated to UE j, $r(b_j)$ is the expected data rate of UE j, which is assumed to be linear with b_j (e.g., as in Shannon capacity), and the payment has a unit of $\log(r(b_j))$. We also have the following constraints.

$$\sum_{j\in\mathcal{L}^E_i} b_j = B^E_i, \ \sum_{j\in\mathcal{L}^C_i} b_j = B - B^E_i, \ \sum_{j\in\mathcal{L}_i} b_j = B. \quad (18)$$

$$r(b_j) = \max\{r(b_j), \epsilon\}, \ \epsilon > 0. \quad (19)$$

In (17), the first term is the maximum total utility of cell center and edge UEs, while the second term is the total utility when PeNB i does not serve cell edge users (failed or not participating in the auction). If $B^E_i = 0$, the payment $\tilde{p}_i = 0$ and the first two terms cancel each other; thus we have $U_i(B^E_i = 0) = 0$. Eq. (19) is to enforce a minimum non–zero value ϵ for $r(b_j)$ so the utility won't be minus infinity.

Assume that spectrum is evenly assigned to UEs, i.e.,

$$b_j = \frac{B^E_i}{|\mathcal{L}^E_i|}, \text{ for } j \in \mathcal{L}^E_i; \text{ and } b_j = \frac{B^C_i}{|\mathcal{L}^C_i|}, \text{ for } j \in \mathcal{L}^C_i, \quad (20)$$

where $|\cdot|$ is the cardinality of a set. Then it can be shown that $U_i(B^E_i)$ is a concave function of B^E_i; it monotonically increases when $B^E_i \leq B \cdot \frac{|\mathcal{L}^E_i|}{|\mathcal{L}^E_i|+|\mathcal{L}^C_i|} \doteq \bar{B}^E_i$. Thus under constraint (18), we have

$$\bar{p}_i = \max\left\{\sum_{j\in\mathcal{L}^E_i}\log(r(b_j)) + \sum_{j\in\mathcal{L}^C_i}\log(r(b_j))\right\} - \max\left\{\sum_{j\in\mathcal{L}_i|B^E_i=0}\log(r(b_j))\right\}$$

as the highest price that PeNB i can offer for the corresponding spectrum request is $\bar{d}_i = \bar{B}^E_i$.

B. Bidding Model and Utility of the Spectrum Holder

The channel selection and bidding procedure is shown in Fig. 4, which works as follows.

1) A PeNB first searches all unlicensed channels for a "clean" one with no Wi–Fi activity, or not occupied by other PeNBs for a given time period. If such a channel is found, the PeNB holds and utilizes the channel.
2) If there is no such "clean" channel, the PeNB searches for a "Wi–Fi–only" channel with only Wi–Fi activities detected for a given time period. If such a channel is found, the PeNB holds and utilizes the channel, using the technique proposed in Section IV.

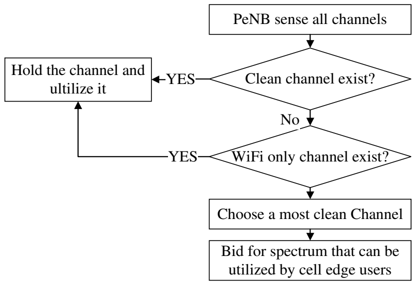

Fig. 4. The channel selection and bidding procedure.

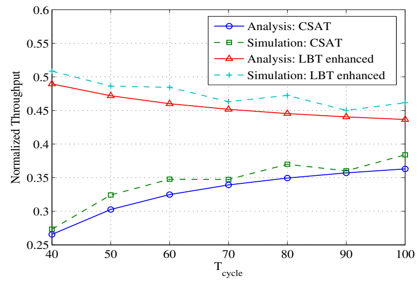

Fig. 5. Normalized Wi-Fi throughput versus length of LTE-U duty cycle T_{cyc}: 3 Wi-Fi stations and $T_{on} = T_{off}$.

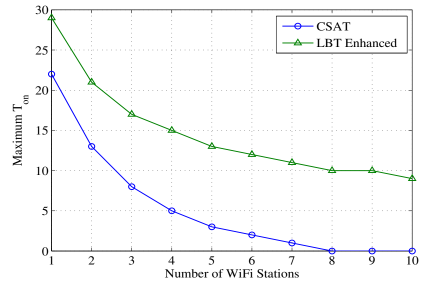

Fig. 6. Maximum T_{on} versus the number of Wi-Fi stations when the coexistence criterion (14) is satisfied: $T_{cyc} = 60$ ms.

3) If neither a "clean" nor a "Wi-Fi-only" channel can be found, the PeNB must participate in an auction for spectrum to serve its cell edge UEs.

To coordinate channel assignment and spectrum auction, we assume that a server holds the auction and exchanges channel holding and spectrum assignment information for PeNBs. The server also enforces the following operating principles for channel holders and auction participators.

- *Channel holder:* To hold channel $i \in \mathcal{H}$, the PeNB first claims it through the auction server. It then monitors the channel and executes its coexistence strategy, i.e., setting T_{on} and T_{off}.[1] In every interval of T, the PeNB should update the coexistence strategy, report to the auction server, and initiate an auction window. At the end of the interval T, the server determines the spectrum assignment and the payment to the channel holder. Note that to be assigned spectrum for cell edge UEs, the channel holder also needs to submit a bid to the auction server. It can use all spectrum for free if there is no other participator.
- *Auction participator:* Let the set of participators be $\mathcal{A}^H$. If a PeNB is interested in accessing channel $i \in \mathcal{H}$, it should always abide by the coexistence strategy. If it needs spectrum for cell edge users, it should evaluate the value of the channel and submit a bid to the auction server. At the end of T, the PeNB makes payment and starts to transmit if it wins some spectrum.

Note that the control messages between PeNBs and the auction server are transmitted through the X2 interface.

Assume the server strategy is to maximize its utility on the basis of maintaining truthful bidding. The social welfare is

$$U = \sum_{i \in \mathcal{A}^H} U_i(\tilde{d}_i) \quad (21)$$

$$\text{s.t.} \;\; I_{i,j}(c^E_{i,k} + c^E_{j,k}) \le 1, \; \forall i,j \in \mathcal{A}^H, \; \forall k \in \mathcal{K}, \quad (22)$$

where $c^E_{i,k}$ is the spectrum assignment indicator: $c^E_{i,k} = 1$ if spectrum k is assigned to PeNB i and $c^E_{i,k} = 0$ otherwise; $\tilde{d}_i = \sum_{k \in \mathcal{K}} c^E_{i,k}$ is the spectrum assigned to PeNB $i \in \mathcal{A}^H$ for its cell edge UEs; the constraint ensures that no neighboring PeNBs be assigned the same spectrum for cell edge UEs.

In each auction, each bidding PeNB $i \in \mathcal{A}^H$ submits a bid in the form of (p_i, d_i), where p_i is the price it is willing to pay and d_i is the amount of spectrum it requests. Then the auction server may approve a bid $(\tilde{p}_i, \tilde{d}_i)$ where

$$\tilde{p}_i \le p_i \text{ and } \tilde{d}_i \le d_i, \;\; \text{and } \tilde{p}_i \le p_i \cdot \tilde{d}_i / d_i. \quad (23)$$

As $U_i(\tilde{d}_i)$ is a concave function of $\tilde{d}_i$, if PeNB i submits a bid $\{p_i, d_i\}$, but a bid $(\tilde{p}_i, d_i \frac{\tilde{p}_i}{p_i})$ is approved, the utility of PeNB i is still positive. Hence a bid $(\tilde{p}_i, \tilde{d}_i)$ that follows (23) will surely achieve a positive utility for PeNB j, providing an incentive for the PeNB to accept the approved bid.

C. Optimal Strategy

To maximize social welfare and ensure truthful bidding, we adopt the Vickrey-Clarke-Groves (VCG) auction model. The VCG auction maximizes social welfare and gives bidders incentives to bid truthfully [22]. The optimal winner set and spectrum allocation problem can be formulated as

$$\max : \sum_{i \in \mathcal{W}^H} p'_i \quad (24)$$

$$\text{s.t.} \;\; p'_i \le p_i \text{ and } d'_i = d_i \cdot p'_i / p_i, \; \forall i \in \mathcal{W}^H \quad (25)$$

$$I_{i,j}(c^E_{i,k} + c^E_{j,k}) \le 1, \; \forall i,j \in \mathcal{A}^H, \; \forall k \in \mathcal{K} \quad (26)$$

$$d'_i = \sum_{k \in \mathcal{K}} c^E_{i,k}, \; \forall i \in \mathcal{W}^H, \quad (27)$$

where $\mathcal{W}^H$ is the winner set and (p'_i, d'_i) is a proportional bid of (p_i, d_i). That is, a fraction of spectrum in a bid can be approved to maximize the social welfare.

The payment of each PeNB i can be calculated as

$$\tilde{p}_i = \max_{\mathcal{A}^H_{-i}} \left\{ \sum_{j \in \mathcal{W}^{H*}} p^*_j \right\} - \sum_{j \in \mathcal{W}^H_{-i}} p'_j, \quad (28)$$

where $\mathcal{A}^H_{-i}$ is the bidding set with PeNB i removed, $\mathcal{W}^{H*}$ and $\tilde{p}^*_j$ are the winner set and optimal price when PeNB i is removed from the auction, respectively, and $\mathcal{W}^H_{-i}$ is the winner set with PeNB i removed. The payment of PeNB i is the maximum difference between the sum of prices when PeNB

[1] Even for a clean channel, the PeNB should still leave some blank frames, i.e., $T_{off} > 0$, for future Wi-Fi stations. To adapt to change of Wi-Fi activities, the coexistence strategy should be adjusted periodically for intervals of T.

i does not participate in the auction, and the sum of prices of all other winners, except PeNB i, in the optimal strategy.

The winner set selection, spectrum allocation, and the payment calculating all require to solve the maximum price problem (24). We need to maximize the price while allowing spectrum reuse among non–interfering PeNBs, which can be proven to be an NP–hard problem, as given in Theorem 1.

Theorem 1. *The maximum price problem in (24) is NP-hard.*

Proof: If we restrict the bidding to the formation that each PeNB bids for all the spectrum, the problem can be reduced to a maximum independent set problem. As the maximum independent set problem is NP–hard, the maximum price problem in (24) is also NP–hard. ∎

We next propose a *heuristic algorithm* to find the sub–optimal solution to the maximum price problem, as follows.

Algorithm 0: Solving the Maximum Price Problem

Step 1: Group PeNBs in $\mathcal{A}^H$ into non–interfering Groups $\mathcal{G}_1, \mathcal{G}_2, ..., \mathcal{G}_Z$ using Algorithm 1 (see next page), where $I_{i,j} = 0$ for $i, j \in \mathcal{G}_z$, for all z.

Step 2: For each non–interfering group $\mathcal{G}_z$, sort the requested amounts of spectrum and delete duplicate numbers, denoted as $\mathcal{D}_z = \{d_{(z,1)}, d_{(z,2)}, ..., d_{(z,S)}\}$. Then derive the price list $\mathcal{P}_z = \{p_{(z,1)}, p_{(z,2)}, ..., p_{(i,S)}\}$, where $p_{(z,S)} = \sum_{j \in \mathcal{G}_z} p'_j$ and $p'_j = p_j \cdot \min\{1, d_{(i,z)}/d_j\}$.

Step 3: Maximize $\sum_{z \in \mathcal{W}^G} p_{(z,S_z)}$ under constraints $\sum_{z \in \mathcal{W}^G} d_{(z,S_z)} \leq K$ and $\mathcal{W}^G \subset \{1, 2, ..., Z\}$ using Algorithm 2. Allocate $D_z = d_{(z,S_z)}$ to the PeNBs in group $z \in \mathcal{W}^G$, where $\mathcal{W}^G$ is the set of winner groups.

Step 4: The total payment for PeNBs in group z can be calculated as $P_z = \max_{j \neq z}\{\sum_{j \neq z} p_{(j,S_j)}\} - \sum_{j \neq z, j \in \mathcal{W}^G} p_{(j,S_j)}$

Step 5: Split payment in each winning group z as $\tilde{p}_j = P_z \cdot p_j \cdot \min(1, \frac{D_z}{b_j}) / \sum_{j \in \mathcal{G}_z}\{p_j \cdot \min(1, \frac{D_z}{b_j})\}$, for $j \in \mathcal{G}_z$.

Algorithm 1: Forming Non–interfering PeNB Groups

For PeNB i, let $F_i = (p_i/d_i, i)$;
Sort $\{F_1, F_2, \ldots, F_{\mathcal{A}^H}\}$ in descending order of p_i/d_i, denote as $\mathcal{F} = F_{(1)}, F_{(2)}, ..., F_{(|\mathcal{A}^H|)}$;
$z = 1$;
while $(\bar{F} \neq \emptyset)$ **do**
  $\mathcal{G}_z = \emptyset$;
  do
    for $(j = 1 \to |\mathcal{F}|)$ **do**
      if $(I_{a,b} = 0$ *for* $a \in \mathcal{G}_z$*, where* b *is index of* $F_{(j)})$ **then**
        Add b into $\mathcal{G}_z$ and delete $F_{(j)}$ in $\mathcal{F}$;
      end
    end
  while *(*$|\mathcal{G}_z|$ *is increased)*;
  $z++$;
end

In the proposed heuristic algorithm, we first group PeNBs into non–interfering groups, so that all the PeNBs in the same group can reuse the same spectrum. The PeNBs in each non–interfering group can share payment in the auction. The PeNBs in the same non–interfering group may submit bids with different prices and spectrum requests. Hence, we derive a list of virtual bids, i.e., price and spectrum combinations, in which the requested spectrum is monotonically increasing and the price for unit spectrum is monotonically decreasing, which will be given in Theorem 2. Then the problem is reduced to selecting a set of virtual bids from the non–interfering groups to maximize the sum of virtual bids, under constraints of total spectrum limitation and at most one virtual bid can be selected from each group, as in Step 3. This problem is an extension of the Knapsack Problem [23] and we propose a *dynamic programming* algorithm to obtain the optimal solution, which is presented in Algorithm 2. With the optimal solution of maximizing $\sum_{i \in \mathcal{W}^G} p_{(i,z_i)}$, we can also obtain the payment for each group. Finally, we split payment among the winning PeNBs in Step 5.

Algorithm 2: Maximizing Social Welfare

Set $F(k) = 0$ and $T(k) = \emptyset$, for all $i = 1 \to K$;
for $(z = 1 \to Z)$ **do**
  for $(k = K \to 1)$ **do**
    $F' = \max\{p_{(z,s)} + F(k - d_{(z,s)})\}$, where $p_{(z,s)} \in \mathcal{P}_z$ and $d_{(z,s)} \in \mathcal{D}_z$;
    if $(F' > F(k))$ **then**
      $F(k) = F'$ and update $T(k)$;
    end
  end
  Output $F(K)$ and $T(K)$;
end

In Algorithm 1, we sort the PeNBs participating in the auction $\mathcal{A}^H$ into non–interfering groups with a greedy approach. We first sort the PeNBs in descending order according to the unit price of bid, i.e., p_i/d_i. Then we select non–interfering PeNBs from the remaining PeNB list, giving priority to high unit price PeNBs. If there is no PeNB in the current remaining list, a new group will be created. The process continues until all PeNBs are grouped. The complexity is $\mathcal{O}(m^3)$, where $m = |\mathcal{A}^H|$ is the number of PeNBs participating in the auction.

In Algorithm 2, we present the optimal algorithm based on dynamic programming. The idea is to use two matrices, $F(k, z)$ and $T(k, z)$, to record the maximum sum of payment and the corresponding spectrum allocation, given that k spectrum is available and the first z groups are already considered. Assume that we have figured out $F(k', z-1)$ for $k' \leq k$, then $F(k, z)$ can be obtained by

$$\begin{aligned} & F(k, z) \\ &= \max\{F(k, z-1), \max\{p_{(z,s)} + F(k - d_{(z,s)}, z-1)\}\}. \end{aligned} \tag{29}$$

That is, to maximize $F(k, z)$, the strategy can be decomposed into a strategy for selecting bids in groups 1 to $(z-1)$ and a strategy for selecting bids in group z. If we do not select any bid in group z, then $F(k, z) = F(k, z-1)$. If we select bid $(p_{(z,s)}, d_{(z,s)})$, then $F(k, z)$ is the payment of

$p_{(z,s)}$ plus the maximum payment in groups 1 to $(i-1)$ with spectrum $k - d_{(z,s)}$ available. It follows that $F(k,z) = p_{(z,s)} + F(k - d_{(z,s)}, z-1)$. In summary, the maximum of $F(k,z)$ can be derived as in (29). Also note that when calculating $F(k,z)$, we only need $F(k', z-1)$ with $k' \leq k$. So we do not need to maintain the two dimensional matrices. Instead, we only need to maintain one dimension matrices $F(k)$ and $T(k)$, in which $F(k)$ is $F(k, z-1)$ before it is updated and become $F(k,z)$ after it is updated.

In Algorithm 2, we first initialize $F(k)$ and $T(k)$. In Line 3, we choose to compute from $k = K$ to 1, because when updating $F(k)$, we need $F(k')$ for $k' \leq k$ remain unchanged. From Line 3 to 6, we update $F(k)$ and $T(k)$, where $F(k)$ is the maximum price and $T(k)$ is the corresponding channel assignment for each group when k spectrum is available. The complexity of Algorithm 2 is $\mathcal{O}(m^2 K)$, where m is the number of PeNBs and K is the number of sub–channels.

The following theorem shows the monotone increasing and decreasing properties of the requested spectrum and unit price, respectively, in the list of virtual bids.

Theorem 2. *If* $d_{(z,s)} \leq d_{(z,s')}$*, then* $\frac{p_{(z,s)}}{d_{(z,s)}} \geq \frac{p_{(z,s')}}{d_{(z,s')}}$.

Proof: If $d_{(z,s)} \leq d_{(z,s')}$, then we have

$$\begin{aligned}
&\frac{p_{(z,s)}}{d_{(z,s)}} - \frac{p_{(z,s')}}{d_{(z,s')}} \\
=&\frac{\sum_{j\in\mathcal{G}_z, d_j < d_{(z,s)}} p_j}{d_{(z,s)}} - \frac{\sum_{j\in\mathcal{G}_z, d_j < d_{(z,s)}} p_j}{d_{(z,s')}} + \\
&\frac{\sum_{j\in\mathcal{G}_z, d_{(z,s')} \leq d_j} p_j \frac{d_{(z,s)}}{d_j}}{d_{(z,s)}} - \frac{\sum_{j\in\mathcal{G}_z, d_{(z,s')} \leq d_j} p_j \frac{d_{(z,s')}}{d_j}}{d_{(z,s')}} + \\
&\frac{\sum_{j\in\mathcal{G}_z, d_{(z,s)} \leq d_j < d_{(z,s')}} p_j \frac{d_{(z,s)}}{d_j}}{d_{(z,s)}} - \frac{\sum_{j\in\mathcal{G}_z, d_{(z,s)} \leq d_j < d_{(z,s')}} p_j}{d_{(z,s')}} \\
\geq& 0.
\end{aligned}$$

■

VI. Simulation Validation

We first validate the analysis of CSAT and LBT enhanced CSAT performance for LTE–U and Wi–Fi coexistence with MATLAB simulations. We then evaluate the proposed sub–optimal algorithm for spectrum sharing among LTE–U PeNBs. We consider an area of 200×200 m^2 and all LTE–U PeNBs and Wi–Fi stations are randomly distributed in the area. We adopted *COST 231 Hata* for metropolitan areas as the propagation model [24]. We consider saturated traffic for both LTE–U users and Wi–Fi stations. LTE–U operates on the 5Ghz band and the channel contains 100 sub–channels. We adopt the same Wi–Fi parameters as in [21]. For simplicity, 1 channel is used in the simulations. We use two benchmark schemes: (i) ICIC with spectrum reuse for cell edge UEs, where PeNBs are grouped so that PeNBs in a group are not neighbors and spectrum is evenly assigned to each group for cell edge UEs; (ii) ICIC without spectrum reuse for cell edge UEs, where the spectrum is evenly assigned to PeNBs for cell edge UEs. The normalized throughput results are as defined in (11) and (13).

We first evaluate the accuracy of our analysis and the performance of Wi–Fi and LTE–U under CSAT and LBT enhanced CSAT. In Fig. 5, we present the impact of the length of CSAT duty cycle, T_{cyc}, on Wi–Fi capacity (see (11)), where T_{on} and T_{off} each takes half of the cycle. Our analysis in Section IV shows that the Wi–Fi performance suffers from collisions between Wi–Fi and LTE–U, which lead to a higher collision rate, lower conditional transmission rate, and hence a lower capacity. This effect is more significant when T_{off} is shorter, which means greater chances of collision between LTE–U and Wi–Fi stations. The simulation results in Fig. 5 clearly validate our analysis; the simulation curves match the analysis curves well. It can be seen that the normalized Wi–Fi throughput of CSAT is considerably lower than that of the proposed LBT enhanced CSAT. When $T_{cyc} = 40$, the CSAT capacity is 0.2655 by analysis and 0.2733 by simulation, while the LBT enhanced CSAT capacity is 0.4896 by analysis and 0.5085 by simulation. The capacity gain achieved by the proposed scheme is 84.4% in analysis and 86.1% in simulation. When $T_{cyc} = 100$, the proposed scheme still achieves over 20% improvements over CSAT. It is also interesting to see that the Wi–Fi capacity with the proposed scheme decreases when T_{cyc} gets larger. This is because Wi–Fi takes some extra transmission time $\mathbb{E}[T_b^*]$ (see (12)) in the LTE–U ON phase, which gets smaller for larger T_{cyc}.

In Fig. 6, we present the relationship between maximum T_{on} and number of Wi–Fi stations, upon the coexistence requirement of in (14) is satisfied. The coexistence between LTE–U and Wi–Fi requires LTE–U to adjust T_{on} and T_{off} to ensure that impact of LTE–U to Wi–Fi stations is no more than adding a Wi–Fi station, as dictated in (14). Hence, LTE–U should have a lower T_{on} with reduced activities on the unlicensed channel when there are more Wi–Fi stations. So our analytical framework provides a useful tool to make LTE–U adaptive to Wi–Fi load for fair coexistence. In addition, when there is one Wi–Fi sation, the CSAT has $T_{on} = 22$, while the proposed scheme has $T_{on} = 29$, with significantly more channel time for LTE–U. When there are 10 Wi–Fi stations, CSAT has $T_{on} = 0$, meaning LTE–U cannot access the unlicensed channel without violating the fairness criterion; while the proposed scheme still has $T_{on} = 9$. Clearly, the LBT enhanced CSAT is a significantly better neighbor to Wi–Fi.

In Fig. 7, we present the relationship between normalized LTE–U capacity (see (13)) and the number of Wi–Fi stations, while satisfying the fairness requirement (14). With more Wi–Fi stations, the T_{on} of LTE–U is reduced, which leads to a lower normalized throughput for LTE–U. As a better neighbor, the proposed LBT enhanced CSAT scheme enjoys a considerably higher normalized throughput. In Fig. 8, we present the corresponding normalized Wi–Fi capacity obtained from the same simulations. The curve marked "Projected" is the projected minimum normalized Wi–Fi throughput when criterion (14) is satisfied. The three curves are very close to each other in the full range, indicating that the Wi–Fi capacity is safely guaranteed by enforcing the fairness criterion.

In Fig. 9, we compare the social welfare of sharing un–

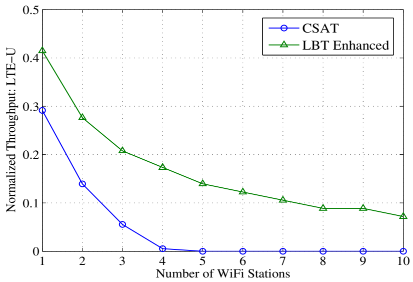

Fig. 7. Normalized throughput of LTE–U versus the number of Wi–Fi stations when the coexistence criterion (14) is satisfied: $T_{cyc} = 60$ ms.

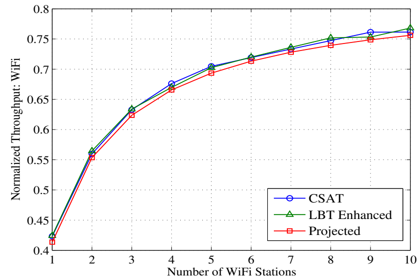

Fig. 8. Normalized Wi–Fi throughput versus the number of Wi–Fi stations when the coexistence criterion (14) is satisfied: $T_{cyc} = 60$ ms.

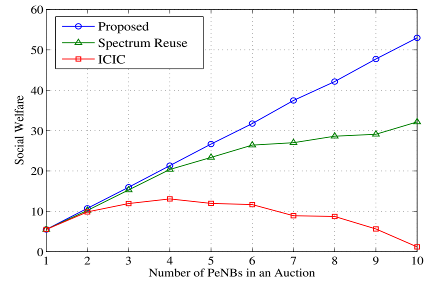

Fig. 9. Number of PeNBs versus social welfare with LBT enhanced CSAT: $T_{on} = 30$ ms, $T_{cyc} = 60$ ms, and 3 Wi–Fi stations.

licensed spectrum among LTE–U PeNBs achieved by the three schemes: (i) the proposed sub–optimal algorithm, (ii) ICIC with spectrum reuse for cell edge UEs, and (iii) ICIC without spectrum reuse for cell edge UEs. It can be seen that for proposed sub–optimal algorithm and ICIC with spectrum reuse strategy, the social welfare increases significantly with increased number of PeNBs. For ICIC without spectrum reuse strategy, the social welfare first increases, then decreases as more PeNBs participating in the auction. This is because the spectrum for edge users could be scarce, which makes the utility of cell edge users turn negative.

VII. Conclusion

In this paper, we presented a systematic approach to the harmonious coexistence of LTE–U and Wi–Fi in unlicensed bands. We first addressed the LTE–U and Wi–Fi coexistence problem with an LBT enhanced CSAT scheme. Through rigorous analysis and simulations, we showed that the proposed scheme can achieve significantly improved capacity for both LTE–U and Wi–Fi, along with guaranteed fairness. We then addressed the problem of spectrum sharing among LTE–U PeNBs with an auction based scheme that incorporated an ICIC mechanism. The analysis and the superior performance of the proposed schemes were validated with simulation and comparison with several benchmarks.

Acknowledgment

This work is supported in part by the NSF under Grants CNS–1320664 and CNS–1702957, and by the Wireless Engineering Research and Education Center at Auburn University.

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