Optimizing Unlicensed Spectrum Sharing for LTE-U and WiFi Network Coexistence

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***Abstract*—Long-term evolution in unlicensed spectrum (LTE-U) is an emerging technology for expanding cellular network capacity without additional spectrum cost. This paper investigates effective spectrum sharing for coexisting Wi-Fi and LTE-U services. Based on a novel hyper access point (HAP) we introduced for effectively embedding LTE-U in unlicensed Wi-Fi band, LTE-U can directly take advantage of the Wi-Fi point coordination function protocol. To facilitate the coexistence, our HAP dedicates a contention-free period to LTE-U users and allows a contention period (CP) for traditional Wi-Fi users. We investigate the optimization of joint user association and resource allocation to further improve system throughput and user fairness. We formulate a network utility maximization problem based on the Nash bargaining solution (NBS), for which we derive a closed-form expression for the optimal CP length under a given user association. We analyze this NBS-based utility maximization and the performance of the proposed algorithm under log-normal fading, Rayleigh fading, and Rician fading channel models, respectively. Our numerical results corroborate our analysis and demonstrate effective improvement of the system performance by the proposed HAP algorithm against traditional LTE-U deployment.**

***Index Terms*—LTE in unlicensed spectrum, adaptive resource allocation, hyper access point, spectrum sharing, Nash bargaining solution, carrier aggregation.**

I. INTRODUCTION

AS THE most successful radio access standards in commercial wireless networks today, both long-term evolution (LTE) and WiFi systems are confronted with the challenges from limited capacity with the exponential growth of mobile data traffic. Many new technologies have been recently developed to improve the spectral efficiency including, among others, massive MIMO, cognitive radio, small cells, and full-duplex communications. Fundamentally, the scarcity of good spectral band is still the major bottleneck. Thus, for both networks, one of the most critical issues is the joint utilization of their collective spectral resources for total capacity enhancement [1].

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Recently, the US Federal Communications Commission authorized an additional 195 MHz unlicensed bandwidth in the 5.8 GHz U-NII band, stimulating substantial interest from both LTE and WiFi providers. In particular, LTE in unlicensed spectrum (LTE-U), also known as licensed-assisted access, has been proposed [2]–[5], and is currently under consideration by the 3rd generation partnership project (3GPP) for its Release 13 [6]. Unlicensed spectrum can be aggregated by small cell base stations (SBSs) to enhance both system throughput [7], [8] and energy efficiency [9]. Furthermore, opportunistic integration of mobile data offloading and LTE-U can potentially achieve substantial throughput gain for cellular networks without adversely affecting WiFi performance [10]. In [11], a strategy mutually beneficial for LTE-U and WiFi systems has been developed by transferring some WiFi users to the LTE-U network to more efficiently utilize the unlicensed spectrum. Other considerations include unlicensed spectrum for device-to-device communications [12], [13].

Despite these recent advances, LTE-U technology still faces stiff challenges before large scale deployment. One problem is that LTE systems were originally designed for licensed spectrum under a centralized user admission and medium access control (MAC) protocol to avoid collision among subscribers, whereas most WiFi systems utilize contention-based MAC through carrier sensing multiple access (CSMA) and distributed coordination function (DCF) protocols to resolve packet collision. Therefore, to implement LTE-U in the unlicensed spectrum, one primary issue is to fairly and harmoniously coexist with the extremely popular incumbent WiFi systems.

Currently, the two major mechanisms for LTE and WiFi coexistence are: (a) listen-before-talk (LBT) and (b) duty-cycle muting (DCM). In LBT, the mechanism of CSMA with collision avoidance is used at SBSs and mobile terminals to compete for an unlicensed channel [14]–[16]. On the other hand, DCM utilizes carrier sensing adaptive transmission (CSAT), with which LTE-U system vacates the unlicensed channel for WiFi users by muting periodically through duty cycle control [17]–[19]. Both LBT parameters and the duty-cycle duration can be adaptively controlled according to measured WiFi traffic volume to regulate inter-system fairness [16]. Beyond these two methods, cognitive radio schemes have also been considered for coexistence [20], and the authors in [21] have proposed the use of different frame structures and multiple antennas for LTE and WiFi to achieve non-orthogonal coexistence. More recently, an unlicensed spectrum inter-cell interference co-ordination (usICIC) mechanism has been developed for multiple LTE-U network coexistence in [22].

One limitation of the aforementioned proposals lies in the need for a centralized controller. Without such an impractical central controller for both LTE-U and WiFi systems, the mutual interference between LTE-U and WiFi networks remains a key obstacle to efficient spectrum utilization in heavily loaded networks. To enhance the efficiency of unlicensed spectrum utilization and achieve better coexistence between LTE-U and WiFi, we have proposed the concept of a novel hyper access point (HAP) in [23]. The HAP is deployed by cellular operators and can serve as both LTE-U SBS and WiFi AP as one node, enabling better coordination of spectrum allocation and interference management. Moreover, unlike DCF based WiFi access mechanism that most current LTE-U networks wish to adopt, the HAP leverages the inherent and more advanced point coordination function (PCF) and hybrid coordination function (HCF) access control mechanisms already available in WiFi networks. In both PCF and HCF access control, each time period on an unlicensed band consists of a contention free period (CFP) and a contention period (CP). The controlled access by CFP is used for LTE-U user transmission by the HAP controller whereas the CP is left open for WiFi transmission using the traditional contention-based access protocol.

Our recent paper [23] provides the basic concept of a novel LTE-U coexistence framework among a number of research works directed at LTE-U. The proposed network provides a new degree of freedom for users to access unlicensed spectrum. Under HAP, users may flexibly associate with either the LTE-U or the WiFi network by taking into account service quality, subscription, and cost. Moreover, the resource division between CFP and CP can be dynamically adapted according to user density, traffic load, and service requirement. Through this approach, the unlicensed channel resource can be more efficiently utilized and the interference between LTE-U and WiFi becomes easier to manage. Perhaps most importantly, *this novel LTE-U and WiFi coexistence framework is backward compatible and non-intrusive as it requires no change to existing WiFi user devices and is amendable to LTE carrier aggregation.*

Based on this novel HAP-based LTE-U framework, we aim to develop detailed analysis and designs with respect to user association and resource allocation. In this paper we investigate means for optimizing user association and resource allocation for LTE-U and WiFi coexistence. We consider a heterogeneous network in which both HAP and traditional WiFi AP operate on the same unlicensed spectrum. Within this heterogeneous network, users served by the HAP (denoted as hybrid users) can access either the LTE-U or the WiFi interface. Thus, one important problem is the optimal access control of each hybrid user for the two spectrum sharing wireless interfaces. A related and equally important question is to optimize allocation of CP and CFP resources to support the dynamically changing distribution of different users.

The major contributions of this work are as follows.

- Based on quality-of-service (QoS) requirements of both LTE-U and WiFi users, we derive an upper bound and a lower bound of the CP length.
- To optimize CP allocation, we utilize the Nash bargaining solution (NBS) to formulate a network utility maximization problem. The closed-form expression for the optimal CP length is derived, and certain inherent properties are also discussed.
- Based on the optimal CP allocation, we analyze the user association problem. Moreover, the NBS-based utility maximization is theoretically compared with other utility functions including overall network throughput and the WiFi throughput.
- The performance of the proposed user association and CP allocation algorithm is analyzed under different channel fading assumptions including: log-normal fading, Rayleigh fading, and Rician fading.
- By leveraging centralized scheduling and channel state information (CSI), the HAP framework demonstrates substantial throughput improvement over traditional LTE-U coexistence mechanism.

We organize the rest of the paper into five sections. Section II describes the HAP framework and introduces both the LTE-U and WiFi models therein. Section III formulates the joint user association and CP allocation problem and presents a solution algorithm. In Section IV, we analyze the performance of the proposed algorithm under several typical channel fading scenarios. We present our numerical test results in Section V to demonstrate the benefit of the proposed frameworks and optimization algorithm. Finally, Section VI concludes the paper.

II. System Model and Problem Description

A. Brief Introduction of the HAP Concept

In [23], we introduced a heterogeneous LTE-U and WiFi framework based by introducing the concept of HAP, which integrates functionalities of both WiFi AP and LTE SBS into one radio unit. The WiFi interface of the HAP works exclusively in the unlicensed band whereas the LTE interface of the HAP can access both licensed and unlicensed bands to communicate.

Unlike existing LTE-U mechanisms, where the default and most common WiFi channel access mechanism known as DCF is assumed, HAP leverages two standard WiFi MAC protocols, namely PCF and HCF, for shared LTE-U and WiFi access without network conflict. Specifically, IEEE802.11e/n/ac standards have defined an MAC that is well suited for LTE-U and WiFi shared access. In PCF and HCF, each CFP is followed by a CP in each periodic access interval, as shown in Fig. 1. HAP can specify CFP for controlled LTE-U radio access while keeping CP for the WiFi radio access. In the CFP, a centralized coordinator at HAP controls LTE-U user access and resource allocation among admitted LTE-U users. Through orthogonal time-frequency allocation, there can be no LTE user collision while all WiFi radios are muted according to IEEE802.11 MAC specification. No interference exists among

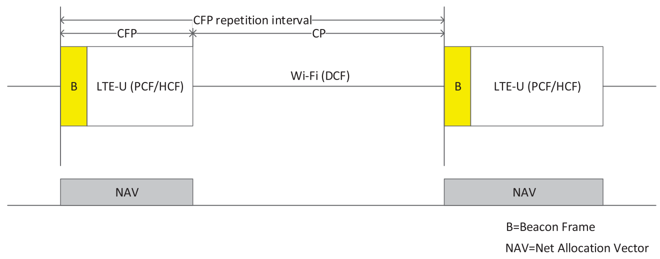

Fig. 1. MAC frame structure of the HAP.

different radios. On the other hand, since radio access periods for LTE and WiFi interfaces are separated, WiFi users no longer need to compete for unlicensed resources with LTE-U users. Hence, the performance of WiFi networks can be separately controlled according to traditional WiFi analysis.

The proposed HAP radio access has three major advantages. First, since HAP is deployed by a single network service provider, it can better mitigate the mutual interference between the two networks through careful frame synchronization (Fig. 1) and management of both licensed and unlicensed bands. Secondly, the central coordinator at HAP can develop more efficient radio resource management strategies by utilizing its CSI knowledge of LTE-U users. Finally, HAP can let users intelligently access LTE-U or WiFi for better QoS guarantee. It can optimally and flexibly control the duty-cycle of CP and CFP to ensure fair coexistence of the two networks and their users.

Therefore, this paper focuses on the user association (or access) and CP allocation within the proposed HAP framework to achieve a fair and efficient coexistence between LTE-U and WiFi.

Presently, there are three major operation modes for LTE-U networking based on different control channel configurations: (a) supplementary downlink (SDL), (b) carrier aggregation (CA) time division LTE (TD-LTE), and (c) standalone LTE-U [2], [3]. The unlicensed spectrum in either the SDL mode or the CA TD-LTE mode is used as an auxiliary channel to transmit data, while control signals still use licensed spectrum. In standalone LTE-U mode, however, both data and control signals must be transmitted on unlicensed spectrum without relying on the additional licensed spectrum. The standalone mode offers a more flexible mean for the LTE-U networking since it does not depend on the availability of licensed spectrum. However, this mode is also the most challenging one due to the absence of licensed spectrum.

In this paper, we focus on the standalone LTE-U scenario in which one HAP and several WiFi APs coexisting on the same unlicensed spectrum, as depicted in Fig. 2. The extension of our work to the other two modes is straightforward, and could be left for future work. We assume M LTE-U users, K hybrid users, and N WiFi users covered by the HAP, denoted as $\mathcal{M} = \{1, 2, \cdots, M\}$, $\mathcal{K} = \{1, 2, \cdots, K\}$, and $\mathcal{N} = \{1, 2, \cdots, N\}$, respectively. The hybrid users are equipped with both LTE-U and WiFi transceivers, while pure LTE-U users and WiFi users only have LTE-U and WiFi transceivers, respectively. The hybrid users associate with either LTE-U or WiFi interface. Specifically, J ($\mathcal{J} = \{1, 2, \cdots, J\}$) of K hybrid

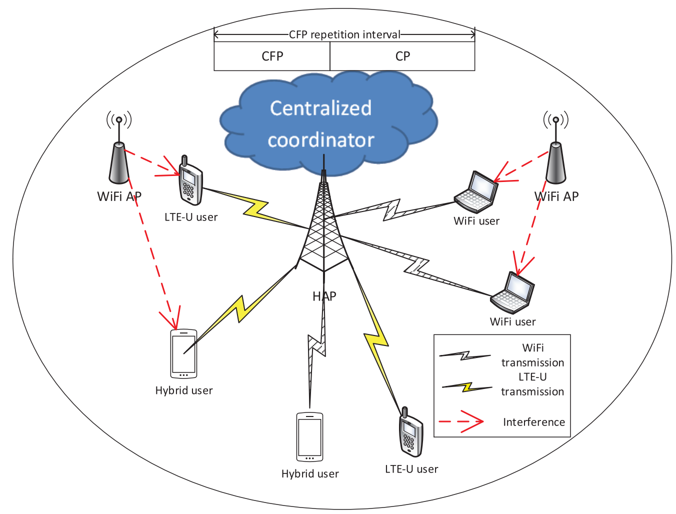

Fig. 2. System model for user association and CP allocation.

users will be associated with the LTE-U interface, whereas the remaining $K - J$ hybrid users will associate with the WiFi interface. Therefore, the M LTE-U users in addition to the J LTE-U hybrid users will be served during the CFP period using the LTE-U interface while the N WiFi users as well as the remaining $K - J$ hybrid users will be served during the CP period using the WiFi interface. We further denote the CFP duration and the CP duration in the CFP repetition interval L as $L - \ell$ and ℓ, respectively.

In this paper, one objective for us is to derive the optimal values for both J and ℓ to meet the performance requirements of the three types of user equipments. Moreover, the selection of hybrid users for association to the LTE-U interface should also be investigated.

B. WiFi Model

Without loss of generality, we consider WiFi in the 5 GHz unlicensed spectrum to be compliant with the IEEE 802.11n protocol. For analysis, we assume that the $N + K - J$ stations are overloaded with full buffers of packets to transmit. Throughout our analysis, we use two performance metrics: WiFi access probability and average throughput.

1) WiFi Access Probability: Let $CW_{\min}$ and $CW_{\max}$, respectively, denote the minimum and maximum contention window sizes as defined in IEEE 802.11. Furthermore,

$$CW_k = \min\left(2^k CW_{\min}, CW_{\max}\right)$$

is the maximum contention window size after k collisions.

Given the $N + K - J$ users associated with the WiFi interface, WiFi access probability $\Pr\{d < \ell | N + K - J\}$ is the probability that WiFi backoff delay is shorter than the CP length, ℓ. We know from [24] that

$$\begin{aligned}
&\Pr\{d < \ell | N + K - J\} \\
&= \sum_{i=0}^{R}\sum_{j=0}^{W_i} \Pr\{d < \ell | i \text{ collisions}, j \text{ slots}\} \\
&\quad \Pr\{j \text{ slots} | i \text{ collisions}\} \Pr\{i \text{ collisions}\}, \qquad (1)
\end{aligned}$$

where R is the retry limit and $W_i = \sum_{k=0}^{i} CW_k - 1$. Note that $\Pr\{j \text{ slots}|i \text{ collisions}\}$ is the probability that the sum of the $i+1$ backoff durations of the packet equals j, and is given by

$$\Pr\{j \text{ slots}|i \text{ collisions}\} = \Pr\left\{\sum_{k=0}^{i} \text{unif}\,(0, CW_k - 1) = j\right\}, \tag{2}$$

where $\text{unif}\,(0, C)$ represents a discrete random variable uniformly distributed in the range of $\{0, 1, \cdots, C\}$, and $\Pr\{i \text{ collisions}\}$ represents the probability that a packet encounters i collisions before being transmitted.

Let τ be the probability that one of the $N+K-J$ stations transmits in a slot time. Then we have

$$\begin{aligned}&\Pr\{i \text{ collisions}\}\\&\quad = \left(1-(1-\tau)^{N+K-J-1}\right)^{i}(1-\tau)^{N+K-J-1}.\end{aligned} \tag{3}$$

Additionally, according to [24], the probability $\Pr\{d < \ell|i \text{ collisions}, j \text{ slots}\}$ can be expressed as a Gaussian distribution with mean m_{ij} and variance δ_{ij}. In other words,

$$\begin{aligned}&\Pr\{d < \ell|i \text{ collisions}, j \text{ slots}\}\\&\quad = \begin{cases}0.5 + 0.5\text{erf}\left(\dfrac{\ell - m_{ij}}{\sqrt{2}\delta_{ij}}\right), & \dfrac{\ell - m_{ij}}{\sqrt{2}\delta_{ij}} \geq 0,\\ 0.5\text{erfc}\left(-\dfrac{\ell - m_{ij}}{\sqrt{2}\delta_{ij}}\right), & \dfrac{\ell - m_{ij}}{\sqrt{2}\delta_{ij}} < 0.\end{cases}\end{aligned} \tag{4}$$

In order to meet a required WiFi access probability threshold $\Pr_T^{w}$, where superscript w denotes WiFi and T denotes a threshold, we should guarantee that

$$\Pr\{d < \ell|N+K-J\} \geq \Pr_T^{w}. \tag{5}$$

In order for the access probability to be unaffected by the presence of LTE-U users, we can select $\Pr_T^{w} = \Pr\{d < L|N+K\}$, which represents the WiFi access probability when all hybrid users are associated with the WiFi interface and when the entire periodic PCF frame is used for the CP only. In other words, we can maintain the same access probability such that the $N+K-J$ WiFi users are oblivious to the network activation of the LTE-U access such that J hybrid users have migrated to the LTE-U interference and that a fraction of the PCF frame has become CFP which is no longer accessible to them.

To design the hybrid network by selecting an optimal ℓ such that the WiFi access probability is unaffected, numerical method can be used to find the minimum required CP length, ℓ_T, to satisfy $\Pr\{d < \ell_T|N+K-J\} \geq \Pr_T^{w}$.

2) WiFi Throughput: Recall that the WiFi network is assumed to be in the overloaded state with saturated buffers. Let T_s be the average time that the unlicensed channel band is sensed as busy because of a successful transmission and let T_c be the average time that the channel is sensed as busy by each station during a collision. Let T_σ be the duration of an empty time slot and $\mathbb{E}[P]$ be the average packet size.

According to [25], the saturation throughput of each WiFi user is simply a function of the number of competing users, given by

$$\begin{aligned}&R(N+K-J)\\&\quad = \frac{\Pr_{\text{tr}}\Pr_{\text{s}}\mathbb{E}[P](N+K-J)^{-1}}{(1-\Pr_{\text{tr}})T_\sigma + \Pr_{\text{tr}}\Pr_{\text{s}}T_{\text{s}} + \Pr_{\text{tr}}(1-\Pr_{\text{s}})T_c},\end{aligned} \tag{6}$$

where $\Pr_{\text{tr}} = 1-(1-\tau)^{(N+K-J)}$ is the probability that at least one transmission takes place in a slot, and $\Pr_{\text{s}} = \dfrac{(N+K-J)\tau(1-\tau)^{N+K-J-1}}{\Pr_{\text{tr}}}$ is the probability that a transmission on the channel is successful.

Although we focus on the fully loaded node scenario and assume no hidden terminal in the WiFi system, our analysis and results can be extended to the scenarios of non-saturated traffic as well as hidden/exposed terminal problems since those systems have similar throughput expressions as (6), according to [26] and [27].

C. LTE-U Model

In this framework, the unlicensed band during CFP is used to serve both the LTE-U users and the LTE-U hybrid users without considering co-channel LTE-U interferences. The signal-to-interference-ratio (SINR) of each user x with a channel power gain g_x to the serving HAP can be written as

$$\gamma_x = \frac{P_t g_x}{BN_0 + I_{Fx}}, \tag{7}$$

where N_0 is the additive Gaussian noise power, B is the bandwidth for each user, and P_t is the transmit power of each user. We use notations $x = m$ to describe the LTE-U users and $x = j$ to describe the LTE-U hybrid users.

Since the unlicensed resources for both LTE-U and WiFi interfaces are separated orthogonally, interference between LTE-U and WiFi users in the same HAP can be neglected in this work. Hence, the sum interference power I_{Fx} from all other WiFi APs and HAPs uncoordinated by the serving HAP can be written as

$$I_{Fx} = P_t \sum_{i \in \Phi/t} g_{ix}, \tag{8}$$

where Φ is the set of all HAPs and WiFi APs, t is the home HAP, and g_{ix} is the fading channel power gain between user x and the $i-$th HAP.

The characteristics of the channel power gains g_x depend on the channel fading models and the CSI knowledge. In Section IV, we shall consider three common channel models in the performance analysis: log-normal fading, Rayleigh fading, and Rician fading. Under different fading models, we investigate the ergodic throughput of LTE-U users, i.e., $\mathbb{E}^0\{R_m\}$, $\forall m \in \mathcal{M}$, based only on statistical knowledge of the fading CSI. The ergodic throughput of LTE-U hybrid users, $\mathbb{E}^1\{R_j\}$, $\forall j \in \mathcal{J}$, can be treated differently according to the CSI knowledge, also to be analyzed in Section IV.

III. Joint User Association and CP Allocation

In this section, we will first analyze the feasible region of the CP length before presenting a joint user association and CP allocation algorithm for the HAP network.

A. Feasible Region of the CP Length

Once activated, the HAP can divide the access repetition interval of duration L into a CP with duration ℓ and a CFP with duration $L-\ell$ for WiFi and LTE-U interfaces, respectively. J of K hybrid users would connect with the LTE-U interface while the remaining $K-J$ hybrid users would associate with the WiFi interface. To meet the QoS needs of users in the LTE-U interface, the following constraints should be guaranteed

$$\sum_{m=1}^{M}\beta_m + \sum_{j=1}^{J}\varphi_j = L-\ell, \tag{9}$$

$$\beta_m \mathbb{E}^0\{R_m\} \geq R_T^0, \quad \forall m \in \mathcal{M}, \tag{10}$$

$$\varphi_j \mathbb{E}^1\left\{R_j\right\} \geq R_T^1, \quad \forall j \in \mathcal{J}, \tag{11}$$

where $\boldsymbol{\beta} = \{\beta_1, \beta_2, \cdots, \beta_M\}$ and $\boldsymbol{\varphi} = \{\varphi_1, \varphi_2, \cdots, \varphi_J\}$ denote the set of unlicensed time resources for LTE-U users and LTE-U hybrid users, respectively, R_T^0 and R_T^1 are the data rate requirements of LTE-U and LTE-U hybrid users in one CFP repetition interval, respectively. Rewriting the above constraints, we can derive an upper bound of the CP length ℓ as

$$\ell \leq L - \sum_{m=1}^{M}\frac{R_T^0}{\mathbb{E}^0\{R_m\}} - \sum_{j=1}^{J}\frac{R_T^1}{\mathbb{E}^1\left\{R_j\right\}}. \tag{12}$$

Similarly, to ensure the performance of WiFi users, the following constraints on the access probability and the per-user throughput should be satisfied

$$\Pr\{d < \ell | N+K-J\} \geq \Pr_T^w, \tag{13}$$

$$\ell \cdot R(N+K-J) \geq R_T^w, \tag{14}$$

where R_T^w is the minimum data rate requirement of WiFi users in each CFP repetition interval.

According to (13) and (14), we can achieve the lower bound of the CP length ℓ as

$$\ell \geq \max\left\{\ell_T, \frac{R_T^w}{R\,(N+K-J)}\right\}, \tag{15}$$

where ℓ_T is the minimum CP duration to satisfy $\Pr\{d < \ell_T | N+K-J\} \geq \Pr_T^w$, as discussed earlier in Section II-B.

By combining (12) and (15), the QoS feasible region for the CP length becomes

$$\max\left\{\ell_T, \frac{R_T^w}{R\,(N+K-J)}\right\} \leq \ell \leq L - \sum_{m=1}^{M}\frac{R_T^0}{\mathbb{E}^0\{R_m\}} - \sum_{j=1}^{J}\frac{R_T^1}{\mathbb{E}^1\left\{R_j\right\}}. \tag{16}$$

This QoS feasible region can help speed up the optimization process.

B. Optimal CP Allocation

We now investigate the optimal CP allocation for a given user association number, J. Intuitively, since LTE-U interface is usually more spectrum efficient than the WiFi interface, to maximize system throughput, all hybrid users should be associated to the LTE-U interface by given sufficiently large CFP duration. However, such a decision will minimize the CP duration, thereby severely degrading the performance of WiFi users. Our objective, therefore, is to design a fair and efficient joint user association and CP optimization so as to balance the dual goals of system throughput and fairness to WiFi users.

To optimize the CP duration, we utilize the NBS to account for fairness in user association and CP allocation. NBS has been widely used as an effective technique to achieve good tradeoff between the individual performance objective and global performance [28]–[30]. To define the NBS objective function, we first introduce utility gains for both LTE-U and WiFi users.

Let β_m be the allocated unlicensed resource for LTE-U user m. Then the utility gain for LTE-U user m is defined as the additional resource that this LTE-U user can acquire, defined as

$$z_m^0 = \beta_m - \frac{R_T^0}{\mathbb{E}^0\{R_m\}}, \quad \forall m \in \mathcal{M}, \tag{17}$$

in which $\frac{R_T^0}{\mathbb{E}^0\{R_m\}}$ is the minimum required resource needed to satisfy its QoS requirement. Similarly, the utility gain for each LTE-U hybrid user can be defined as

$$z_j^1 = \varphi_j - \frac{R_T^1}{\mathbb{E}^1\left\{R_j\right\}}, \quad \forall j \in \mathcal{J}, \tag{18}$$

which is the additional resource that the LTE-U hybrid user j can achieve.

With respect to the WiFi users, we can regard the entire WiFi user group as a whole. Thus, the utility gain for WiFi users for a given CP length, ℓ, is defined as

$$z^w = \ell - \frac{R_T^w}{R(N+K-J)}. \tag{19}$$

This utility gain is the additional CP length accounting for the minimum throughput requirement.

To formulate the NBS-based problem, we will first introduce the definition of NBS.

Definition: Z^{NBS} is a NBS if and only if it satisfies the following four axioms: Pareto optimality, independence from irrelevant alternatives, invariant to affine transformations, and symmetry [31].

The existence of NBS to our problem that satisfies the above axioms has been proved in [31]. Since our practical objective is to design a fair and efficient joint user association and CP optimization algorithm to achieve the dual objectives of high system throughput and QoS fairness to WiFi users, the NBS-based utility maximization problem would maximize the product of z^w, z_m^0, and z_j^1 as follows

$$Z^{\text{NBS}} = \max_{\{\ell,\boldsymbol{\beta},\boldsymbol{\varphi},J\}} z^w \prod_{m=1}^{M} z_m^0 \prod_{j=1}^{J} z_j^1, \tag{20a}$$

$$\text{subject to (9), (10), (11), (13), (14), and}$$
$$z^w \geq 0, \quad z_m^0 \geq 0, \ \forall m \in \mathcal{M}, \quad z_j^1 \geq 0, \quad \forall j \in \mathcal{J}. \tag{20b}$$

Since it is quite challenging to solve the above NBS problem, we can transform (20a) into an equivalent but more tractable one

$$\widetilde{Z}^{\mathrm{NBS}} = \ln Z^{\mathrm{NBS}} = \max_{\{\ell,\boldsymbol{\beta},\boldsymbol{\varphi},J\}} \ln\left(\ell - \frac{R_T^w}{R(N+K-J)}\right) + \sum_{j=1}^{J}\ln\left(\varphi_j - \frac{R_T^1}{\mathbb{E}^1\left\{R_j\right\}}\right). \tag{21}$$

To obtain the optimal values of ℓ, $\boldsymbol{\beta}$, and $\boldsymbol{\varphi}$ for a given number of LTE-U hybrid users, J, we first present the following theorem.

Theorem 1: Given J LTE-U hybrid users, the optimal CP length can be expressed as

$$\ell^*(J) = \frac{1}{M+J+1} \times \left(L + (M+J)\frac{R_T^w}{R\,(N+K-J)} - \sum_{m=1}^{M}\frac{R_T^0}{\mathbb{E}^0\{R_m\}} - \sum_{j=1}^{J}\frac{R_T^1}{\mathbb{E}^1\left\{R_j\right\}}\right). \tag{22}$$

Furthermore, the optimal amount of unlicensed resources for LTE-U and LTE-U hybrid users are given, respectively, by

$$\beta_m^*(J) = \frac{1}{M+J+1} \times \left(L - \frac{R_T^w}{R\,(N+K-J)} - \sum_{m=1}^{M}\frac{R_T^0}{\mathbb{E}^0\{R_m\}} - \sum_{j=1}^{J}\frac{R_T^1}{\mathbb{E}^1\left\{R_j\right\}}\right) + \frac{R_T^0}{\mathbb{E}^0\{R_m\}}, \forall m \in \mathcal{M}, \tag{23}$$

$$\varphi_j^*(J) = \frac{1}{M+J+1} \times \left(L - \frac{R_T^w}{R\,(N+K-J)} - \sum_{m=1}^{M}\frac{R_T^0}{\mathbb{E}^0\{R_m\}} - \sum_{j=1}^{J}\frac{R_T^1}{\mathbb{E}^1\left\{R_j\right\}}\right) + \frac{R_T^1}{\mathbb{E}^1\left\{R_j\right\}}, \forall j \in \mathcal{J}. \tag{24}$$

Proof: See Appendix A. $\boxdot$

According to Theorem 1, we can further derive the following corollary to demonstrate that the optimal duration of CP decreases with the number of LTE-U hybrid users, which is proved in Appendix B.

Corollary 1: $\ell^*(J)$ is a strictly decreasing function of J.

This result is rather intuitive since more unlicensed resources are required to serve a larger number of LTE-U hybrid users. In order words, when more hybrid users are associated to the LTE-U interface, larger CFP duration should be allocated, and thereby the CP duration for the WiFi interface should decrease.

C. Optimal User Association

Having established the optimal CP duration for given J LTE-U hybrid users, we now investigate the user association to determine the optimal value of J.

Substitution of (22)-(24) into (21) leads to the optimal NBS function

$$\begin{aligned}\widetilde{Z}^{\mathrm{NBS}} &= \max_J \widetilde{z}^{\mathrm{NBS}}(J)\\ &= \max_J \ (M+J+1) \times \ln\left[\frac{1}{M+J+1}\left(L - \frac{R_T^w}{R\,(N+K-J)} - \sum_{m=1}^{M}\frac{R_T^0}{\mathbb{E}^0\{R_m\}} - \sum_{j=1}^{J}\frac{R_T^1}{\mathbb{E}^1\left\{R_j\right\}}\right)\right].\end{aligned} \tag{25}$$

It is clear from (25) that the optimal number of LTE-U hybrid users J^* can be found by an enumerative search of positive integers. In what follows, we introduce an interesting property for the optimal value.

Define Z^{tot} as the maximal utility gain of the whole system, which can be expressed as

$$\begin{aligned}Z^{\mathrm{tot}} &= \max_J z^{\mathrm{tot}}(J)\\ &= \max_J \sum_{m=1}^{M}\left(\beta_m - \frac{R_T^0}{\mathbb{E}^0\{R_m\}}\right) + \sum_{j=1}^{J}\left(\varphi_j - \frac{R_T^1}{\mathbb{E}^1\left\{R_j\right\}}\right) + \left(\ell - \frac{R_T^w}{R(N+K-J)}\right)\\ &= \max_J L - \frac{R_T^w}{R\,(N+K-J)} - \sum_{m=1}^{M}\frac{R_T^0}{\mathbb{E}^0\{R_m\}} - \sum_{j=1}^{J}\frac{R_T^1}{\mathbb{E}^1\left\{R_j\right\}}.\end{aligned} \tag{26}$$

Here we have applied the equality $\sum_{m=1}^{M}\beta_m + \sum_{j=1}^{J}\varphi_j = L - \ell$.

Remark 1: Z^{tot} is the maximum total utility gain of the entire system without considering the fairness for LTE-U and WiFi users. Because LTE-U interface will always achieve higher spectral efficiency than WiFi, the most number of hybrid users would be associated with the LTE-U interface to yield the largest overall system throughput.

We can also define the maximal utility gain of the WiFi users, as

$$\begin{aligned}Z^w &= \max_J z^w(J)\\ &= \max_J \frac{1}{M+J+1} \times \left(L - \frac{R_T^w}{R\,(N+K-J)} - \sum_{m=1}^{M}\frac{R_T^0}{\mathbb{E}^0\{R_m\}} - \sum_{j=1}^{J}\frac{R_T^1}{\mathbb{E}^1\left\{R_j\right\}}\right).\end{aligned} \tag{27}$$

Let J^w and J^t be the optimal numbers of the LTE-U hybrid users to achieve Z^w and Z^{tot}, respectively. Then, we have the following result.

Theorem 2: When $Z^w \leq 1$, we have $J^* < J^w < J^t$. Otherwise, we have $J^w < J^* < J^t$.

Proof: See Appendix C. ⊡

Remark 2: As mentioned in Remark 1, associating the maximum number of hybrid users to the LTE-U interface would maximize $z^{\text{tot}}(J)$. Therefore, J^t will be the largest. The relationship between J^w and J^* depends on the system environment. When the WiFi network is overcrowded such that $Z^w \leq 1$, fewer hybrid users should be associated to the LTE-U component using less CFP to ensure fairness in the NBS-based utility function, that is, $J^* < J^w$. On the other hand, when the WiFi interface is less crowded, i.e., $Z^w > 1$, to ensure fairness as well as improve system performance, the central controller can assign more hybrid users to the LTE-U interface and increase CFP to maximize $\widetilde{z}^{\text{NBS}}(J)$. Therefore, $J^* > J^w$.

IV. Performance Analysis

To understand the performance advantage of the proposed scheme, we now analyze the system throughput of LTE-U users in the HAP heterogeneous network. We consider three well-known channel fading models: log-normal fading, Rayleigh fading, and Rician fading. We will also compare the performance with more traditional LTE-U proposals. Note that the proposed HAP is deployed by cellular operators and jointly serves as both LTE-U SBS and WiFi AP in one networking unit. As a result, the central scheduler within the HAP can obtain the CSI of both LTE and WiFi users, just like in practical and traditional LTE and 802.11 networks.

A. Ergodic Throughput Analysis

We first analyze the ergodic throughput of LTE-U users, i.e., $\mathbb{E}^0\{R_m\}$, $\forall m \in \mathcal{M}$, which certainly affects the optimal choices of the CP duration ℓ and the user association J in the optimization formulation of (20a) in Section III. Let d_m denote the propagation distance from the $m-$th LTE-U user and let α be the large scale propagation channel loss exponent. We consider that each interference channel is Gaussian distributed. That is, $I_{Fm} = P_t \sum_{i \in \Phi/t} g_{im}$ has the chi-squared distribution with $\phi - 1$ degrees of freedom where ϕ is the total number of all HAPs and WiFi APs. Let $f_{I_{Fm}}(z)$ denote the probability density function (PDF) of I_{Fm}.

Define $q_m = \frac{P_t g_m}{BN_0 + I_{Fm}}$, then the PDF of q_m can be expressed as

$$
\begin{aligned}
&f_Q(q_m) \\
&= P_t \int_0^\infty f_G(yq_m)\, y f_{I_{Fm}}(P_t y - BN_0)\, \mathrm{d}y, \forall m \in \mathcal{M}, \quad (28)
\end{aligned}
$$

where $f_G(g_m)$ represents the PDF of the channel power gain g_m. For different channel models, we have the following expressions for $f_G(g_m)$.

1) *Log-normal fading:* We first consider the log-normal fading channel model. The log-normally distributed channel power gain g_m has the PDF of [32], [33]

$$
f_G(g_m) = \frac{1}{g_m\sqrt{2\pi\sigma_{g_m}^2}} \exp\left(-\frac{\left(\ln g_m - \mu_{g_m}\right)^2}{2\sigma_{g_m}^2}\right), \quad (29)
$$

where μ_{g_m} and $\sigma_{g_m}^2$ are the mean and variance of $\ln g_m$.

2) *Rayleigh fading:* For Rayleigh fading channel, the channel power gain has a PDF of

$$
f_G(g_m) = \mu \exp(-\mu g_m)\, u(g_m), \quad (30)
$$

where $u(g_m)$ is the step function. We shall also take into account the distance-based large scale fading. In this way, we can rewrite the PDF of channel power gain as

$$
\begin{aligned}
&f_Q(q_m) \\
&= P_t d_m^{-\alpha} \int_0^\infty f_G(yq_m)\, y f_{I_{Fm}}\left(P_t d_m^{-\alpha} y - BN_0\right) \mathrm{d}y,
\end{aligned}
$$

where d_m is the distance between user m and the HAP.

3) *Rician fading:* For the Rician fading model, the channel power gain has a chi-square distribution with 2 degrees of freedom, which can be expressed as [35]

$$
\begin{aligned}
f_G(g_m) = &\frac{1}{\Gamma}\left(1 + \frac{\rho}{2\sigma^2}\right) \\
&\times \exp\left(-\left(\frac{\rho}{2\sigma^2} + \left(1 + \frac{\rho}{2\sigma^2}\right)\frac{g_m}{\Gamma}\right)\right) \\
&\times I_0\left(2\sqrt{\frac{\rho}{2\sigma^2}\left(1 + \frac{\rho}{2\sigma^2}\right)\frac{g_m}{\Gamma}}\right), \quad (31)
\end{aligned}
$$

where Γ is the mean value of g_m, $2\sigma^2$ is the predicted mean power of the multipath signal, ρ denotes the peak amplitude of the dominant signal, and $I_0(\cdot)$ is the modified Bessel function of the first kind and zero order.

Therefore, the ergodic throughput of LTE-U user m has a general expression of

$$
\begin{aligned}
\mathbb{E}^0\{R_m\} &= B\mathbb{E}\left\{\log_2\left(1 + \frac{P_t}{BN_0 + I_{Fm}} g_m\right)\right\} \\
&= B\int_0^\infty \log_2(1 + q_m)\, f_Q(q_m)\, \mathrm{d}q_m, \quad \forall m \in \mathcal{M}. \quad (32)
\end{aligned}
$$

B. Performance Comparison

Since user CSI is available at the proposed HAP network even during WiFi connection, hybrid users with better CSI can be associated to the LTE-U interface for better gain. On the other hand, traditional LTE-U networks are unaware of the CSI of hybrid users before they are associated with the LTE-U. Hence, hybrid users can only be randomly associated first.

We now investigate the throughputs of LTE-U hybrid users with and without the available CSI for LTE-U association.

1) CSI-Based User Association: Let $\gamma_1^o, \gamma_2^o, \cdots, \gamma_K^o$ be the independent and non-identical SINR of K hybrid users. By arranging γ_k^o in a non-increasing order, we select J hybrid users with the best SINR for association with the LTE-U interface, i.e., $\{\gamma_1, \gamma_2, \cdots, \gamma_J\}$, where

$$
\gamma_1 > \gamma_2 > \cdots > \gamma_J > \gamma_{J+1} > \cdots > \gamma_K.
$$

Let $q_k(x)$ and $Q_k(x)$ denote the PDF and the cumulative distribution function (CDF) of γ_k^o, respectively. Then, $q_k(x)$ in log-normal and Rician fading models are similar with (28), which can be expressed as

$$q_k(x) = P_t \int_0^\infty f_G(yx)\, y f_{I_{Fk}}(P_t y - BN_0)\,\mathrm{d}y, \quad \forall k \in \mathcal{K}, \tag{33}$$

while in Rayleigh fading model, it has the expression of

$$q_k(x) = P_t d_k^{-\alpha} \int_0^\infty f_G(yx)\, y f_{I_{Fk}}\left(P_t d_k^{-\alpha} y - BN_0\right)\mathrm{d}y, \quad \forall k \in \mathcal{K}. \tag{34}$$

Practically, SINR of hybrid users are independent of each other. It is known [36] that the PDF of the j-th largest SINR among K hybrid users can be expressed as

$$q_\gamma^{(j)}(x) = \sum_{l=1}^{K} q_l(x) \times \sum_{i_1,\cdots,i_{K-1}\in\Delta} \left[\prod_{a=1}^{K-j} Q_{i_a}(x) \prod_{b=K-j+1}^{K-1}\left(1 - Q_{i_b}(x)\right)\right], \tag{35}$$

where

$$\Delta = \left\{ (i_1, i_2, \cdots, i_{K-1}) : \begin{array}{r} 1 \le i_m \le K, \quad i_m \ne l, \\ m = 1, \cdots K-1 \\ i_1 \ne i_2 \ne \cdots \ne i_{K-1} \\ i_1 < i_2 < \cdots < i_{K-j}, \\ i_{K-j+1} < \cdots < i_{K-1} \end{array} \right\}.$$

Therefore, the ergodic throughput of the j-th LTE-U hybrid user is given by

$$\mathbb{E}_{\mathrm{HAP}}^1\{R_j\} = B \int_0^\infty \log(1+x)\, q_\gamma^{(j)}(x)\,\mathrm{d}x, \quad \forall j \in \mathcal{J}. \tag{36}$$

2) Random Association: In this case, the PDF of LTE-U hybrid user j with both log-normal and Rician fading models can be expressed as (33), while for Rayleigh fading model, it can be expressed as (34). Thus, the ergodic throughput of LTE-U hybrid user j under random selection method can be expressed as

$$E_{\mathrm{random}}^1\{R_j\} = B \int_0^\infty \log(1+x)\, q_j(x)\,\mathrm{d}x, \quad \forall j \in \mathcal{J}. \tag{37}$$

V. Numerical Results

In this section, simulation results are presented to evaluate the performance of the proposed joint user association and CP allocation algorithm. We assume that WiFi users, LTE-U users, and hybrid users all follow the Poisson spatial point distribution within circular coverage of the HAP. Unless otherwise specified, we let the numbers of WiFi users, LTE-U users, and hybrid users be 5, 20, and 40. Moreover, WiFi APs that cause interference to the HAP are also randomly distributed around the HAP according to the Poisson spatial point process. The transmit power at the HAP is 20 dBm.

We let the HAP have a radius of 60 m and the length of the PCF repetition interval to be 100 ms (equal to the default setting in IEEE802.11n). Furthermore, we assume that LTE-U, WiFi, and hybrid users have the same minimum data rate requirement of 5 Mbit/s. We adopt the IEEE 802.11n CSMA protocol with the RTS/CTS mechanism working at the 5 GHz unlicensed spectrum in the simulations. Other parameters are listed in Table I. Here, we assume that the channel data rate of the IEEE 802.11n system is 130 Mbps, which is a typical value for 20 MHz bandwidth.

TABLE I
System Parameters

Parameters	Settings
Noise power	−174 dBm/Hz
Path loss exp. α	5
Transmit power	30 dBm
$\mathbb{E}[P]$	1500 byte
B	20 MHz
$CW_{\min}$	16
$CW_{\max}$	1024
R_{limit}	6
WiFi channel bit rate	130 Mbps
PHY header	192 bits
MAC header	224 bits
T_δ	20 μs
SIFS	16 μs
DIFS	50 μs
Slot time	9 μs
ACK	112 bits + PHY header
RTS	160 bits + PHY header
CTS	112 bits + PHY header

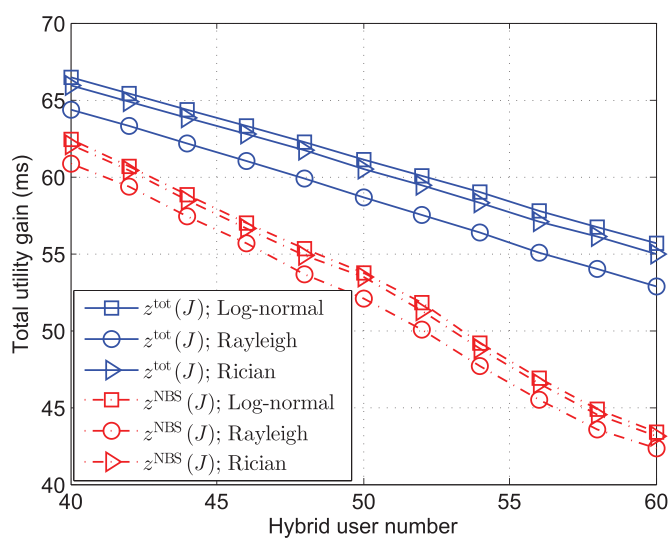

Fig. 3. Total utility gain for the algorithms maximize $z^{\mathrm{NBS}}(J)$ or $z^{\mathrm{tot}}(J)$.

A. Total Throughput Performance

We first show the total utility gain in both LTE-U and WiFi interfaces for different objective functions and different channel fading models in Fig. 3. From the results in the figure,

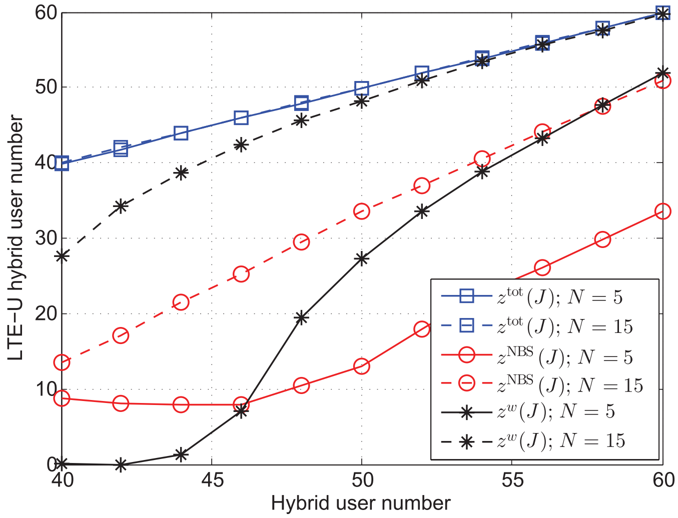

Fig. 4. Optimal number of LTE-U hybrid users for different algorithms.

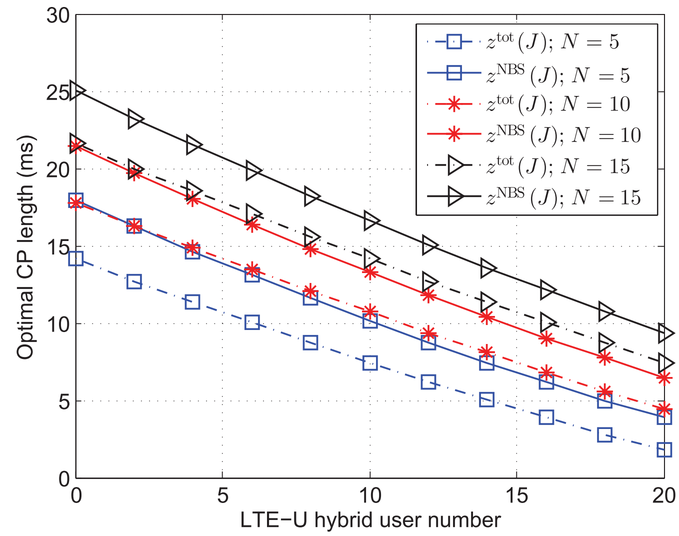

Fig. 5. Relationship between the optimal CP duration and LTE-U hybrid user number for the algorithms to maximize $z^{\mathrm{NBS}}(J)$ and $z^{\mathrm{tot}}(J)$.

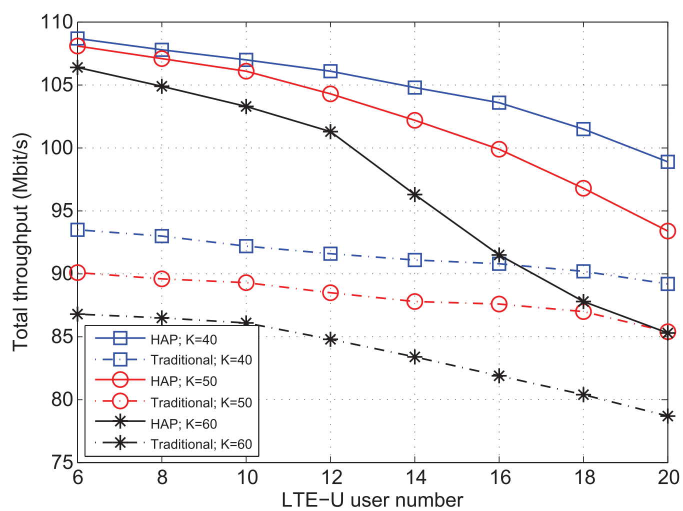

Fig. 6. Total throughput for both CSI-based and random strategies with the proposed NBS-based algorithm.

log-normal fading channels achieve the best performance gain without small scale fading. Under small scale channel fading, the Rician fading model exhibits a larger total utility gain than the Rayleigh fading owing to the line-of-sight channel component. In addition, the total utility gain of the NBS algorithm is below the maximum achieved Z^{tot}. Such result is rather intuitive since the proposed NBS algorithm takes into account the fairness between WiFi and LTE-U users. To provide performance guarantee for the WiFi users, larger CP length may be allocated to the WiFi interface while more hybrid users may be associated to the LTE-U interface.

B. Optimized Number of Hybrid User Association

To avoid redundancy, we consider only the log-normal fading channel model in this set of tests. In Fig. 4, we show the optimal number of LTE-U hybrid users for different objective functions of $z^{\mathrm{NBS}}(J)$, $z^{\mathrm{tot}}(J)$, and $z^{w}(J)$, as well as for different number of LTE-U hybrid users. We let $R_T^w = 10$ Mbit/s. Given the results in this figure, to balance the performance among users, more hybrid users should be associated with the LTE-U interface when the overall number of hybrid users increases. Since $z^{\mathrm{tot}}(J)$ increases with J, the optimal number of LTE-U hybrid users to maximize $z^{\mathrm{tot}}(J)$ is exactly the number of overall hybrid users, i.e., K. Considering the algorithms to maximize $z^{\mathrm{NBS}}(J)$ and $z^{w}(J)$, the optimal number of LTE-U hybrid users increases with WiFi user number, N. Moreover, the optimal number of LTE-U hybrid users for maximizing $z^{\mathrm{NBS}}(J)$ is larger than that for maximizing $z^{w}(J)$ when the total hybrid user number is below a threshold. Note that in this case, we have $Z^{w} \leq 1$. In contrast, the optimal number of LTE-U hybrid users for maximizing $z^{\mathrm{NBS}}(J)$ becomes smaller than that for maximizing $z^{w}(J)$ when the total hybrid user number is above that threshold. This result verifies the conclusions of Theorem 2.

C. Contention Period Optimization

Fig. 5 illustrates the relationship between the optimal CP duration and the number of LTE-U hybrid users. From the figure, the optimal CP duration obtained by the algorithm to achieve Z^{NBS} decreases with the number of LTE-U hybrid users, which confirms Corollary 1. The optimal CP duration to achieve Z^{NBS} is larger than the optimal CP duration to achieve Z^{tot}. This is because larger CP length needs to be allocated to ensure fairness between WiFi and LTE-U users in the NBS algorithm. We can also observe that the optimal CP duration grows with the number of WiFi users. This is intuitive from the fact that the WiFi interface needs more unlicensed resource than the LTE-U interface in order to support equal number of users.

D. HAP Performance Gain

Fig. 6 shows the total throughput of the WiFi and the LTE-U interfaces obtained by using the proposed NBS-based algorithm. We compare the performances of the proposed heterogeneous network and more traditional LTE-U coexistence schemes. From the results in this figure, we observe a significant performance improvement of our proposal which benefits from the exploitation of CSI at the HAP. Note that

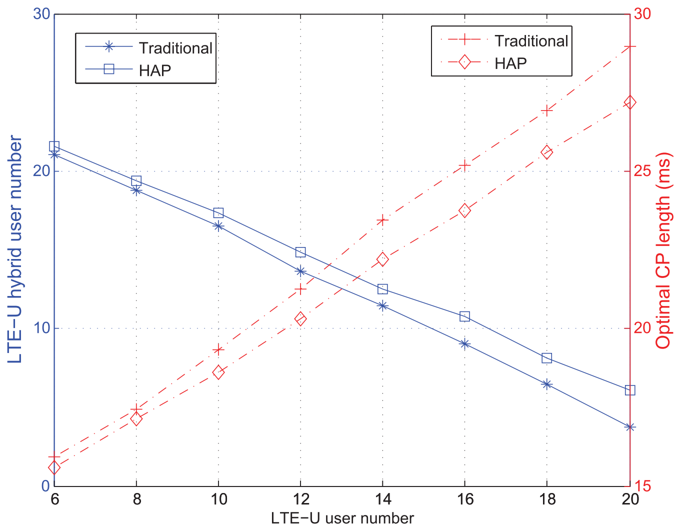

Fig. 7. The number of LTE-U hybrid users and optimal CP length with CSI-based and random strategies.

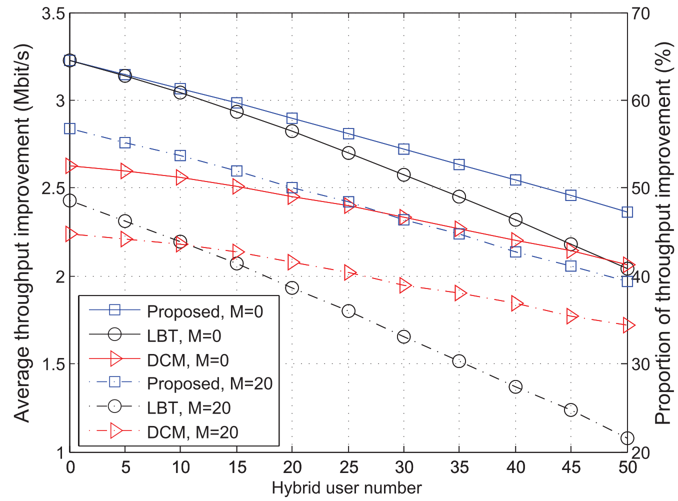

Fig. 8. Performance comparison between the proposed mechanism, LBT, and DCM.

the HAP can obtain the CSI for user association and resource allocation in a centralized way, while the traditional coexistence schemes without WiFi and LTE-U integration cannot benefit from CSI across the two interfaces. On the other aspect, the total throughput slightly drops with growing numbers of LTE-U users as well as hybrid users. This is because that, to ensure fairness, more hybrid users will be associated with the WiFi interface as their number grows.

Fig. 7 further shows that the number of LTE-U hybrid users in the HAP framework is greater than that in traditional LTE-U networks. At the same time, the optimal CP duration is smaller. The reason for such outcomes is quite clear. In the proposed HAP framework, CSI can be exploited for user association such that those hybrid users with stronger channel gains will be selected for LTE-U access. Therefore, more hybrid users will be associated with LTE-U interface to balance fairness with overall system throughput. More LTE-U users would require longer CFP, thereby resulting in the decrease of the optimal CP length. On the other hand, we can observe that the number of LTE-U hybrid users decreases while the optimal CP length increases with a growing number of WiFi users that demands longer CP duration for service.

Fig. 8 presents the performance comparison between the proposed mechanism and two other traditional LTE and WiFi coexistence mechanisms, namely, LBT and DCM, in terms of the average throughput improvement. In DCM, we assume that LTE-U and WiFi are given equal time slots to transmit. From the test results, our proposed mechanism always provides the best performance that is much higher than the other two traditional schemes. The performance gap becomes more evident with growing number of served users. Since the amount of available unlicensed resources decreases with the number of users in the system, the average throughput improvement also declines accordingly. Moreover, when the number of users in the system is small, LBT presents better performance than DCM. When the user number is large, DCM becomes better than LBT. The reason is that, in low density scenarios, the network load is small and users would rarely cause signal collision. Therefore, LBT is quite efficient, and the proposed mechanism does not exhibit substantial advantage. However, in such situation the unlicensed resource for WiFi transmission cannot be exploited very well by the DCM mechanism.

VI. Conclusion

This paper investigates the optimization in terms of user association and resource allocation under a novel HAP framework for the deployment of LTE in unlicensed spectrum occupied by incumbent WiFi users. Our optimization aims to improve the performance of LTE-U and WiFi coexistence within the HAP framework. To avoid disrupting legacy WiFi users, we adopt HCF and PCF access protocols already standardized in the IEEE 802.11n protocol to divide the unlicensed spectrum into CP for WiFi transmission and CFP for LTE-U transmission. By eliminating WiFi and LTE-U interferences without changing the compatibility with legacy WiFi user devices, spectral efficiency of unlicensed band can be further improved by the more efficient LTE-U. Within the HAP framework, we have further emphasized on the joint user association and CP allocation problem to enhance the system throughput and user fairness. We also derive a closed-form expression for the optimal CP length to maximize the NBS-based network utility function. Our results demonstrate the effective improvement of the novel heterogeneous network when compared with more traditional LTE-U deployment in the presence of WiFi users.

Future works may consider multiple HAPs deployed by competing LTE-U operators. When there are more than one LTE-U operators utilizing HAPs, two scenarios can be considered: orthogonal channels versus non-orthogonal channels. For orthogonal channels, each service provider's HAP is independent with others. Therefore, our proposed functions and solutions remain unchanged. In the United States, there are as many as 3 orthogonal 20 MHz channels (No. 1, 6, and 11) at 2.4 GHz ISM band and 9 such channels in the U-NII band of 5 GHz. Thus, multiple LTE-U service providers can be easily accommodated. The more interesting direction of our future work includes plan to investigate multiple interfering HAP scenarios. In such cases, each offloaded hybrid user can be associated with the LTE-U interface with the best CSI, and the overall benefits of the population of served users should be taken into account by the LTE-U providers when solving NBS-based utility maximization problem.

Appendix A
Proof of Theorem 1

Setting the first-order derivative of (21) on β_m as zero, we can express the optimal β_m as

$$\beta_m = \frac{1}{2}\left[L - \sum_{m'=1,m'\neq m}^{M}\beta_{m'} - \sum_{j=1}^{J}\varphi_j - \frac{R_T^w}{R\left(N+K-J\right)} + \frac{R_T^0}{\mathbb{E}^0\left\{R_m\right\}}\right], \quad \forall m \in \mathcal{M}. \tag{38}$$

Similarly, the optimal φ_j has the closed-form expression of

$$\varphi_j = \frac{1}{2}\left[L - \sum_{m=1}^{M}\beta_m - \sum_{j'=1,j'\neq j}^{J}\varphi_{j'} - \frac{R_T^w}{R\left(N+K-J\right)} + \frac{R_T^1}{\mathbb{E}^1\left\{R_j\right\}}\right], \quad \forall j \in \mathcal{J}. \tag{39}$$

Further, by summating both sides of (38) from $m = 1$ to M, we can obtain

$$(M+1)\sum_{m=1}^{M}\beta_m = M\left[L - \sum_{j=1}^{J}\varphi_j - \frac{R_T^w}{R\left(N+K-J\right)}\right] + \sum_{m=1}^{M}\frac{R_T^0}{\mathbb{E}^0\left\{R_m\right\}}, \tag{40}$$

and by summating both sides of (39) from $j = 1$ to J, we can obtain

$$(J+1)\sum_{j=1}^{J}\varphi_j = J\left[L - \sum_{m=1}^{M}\beta_m - \frac{R_T^w}{R\left(N+K-J\right)}\right] + \sum_{j=1}^{J}\frac{R_T^1}{\mathbb{E}^1\left\{R_j\right\}}. \tag{41}$$

From (9), (40), and (41), we can get the optimal CP ℓ for a given J as

$$\ell(J) = \frac{1}{M+J+1} \times \left(L + (M+J)\frac{R_T^w}{R\left(N+K-J\right)} - \sum_{m=1}^{M}\frac{R_T^0}{\mathbb{E}^0\left\{R_m\right\}} - \sum_{j=1}^{J}\frac{R_T^1}{\mathbb{E}^1\left\{R_j\right\}}\right). \tag{42}$$

Moreover, from (38) and (39), β_m and φ_j can be calculated as

$$\beta_m = \ell - \frac{R_T^w}{R\left(N+K-J\right)} + \frac{R_T^0}{\mathbb{E}^0\left\{R_m\right\}}, \quad \forall m \in \mathcal{M}, \tag{43}$$

and

$$\varphi_j = \ell - \frac{R_T^w}{R\left(N+K-J\right)} + \frac{R_T^1}{\mathbb{E}^1\left\{R_j\right\}}, \quad \forall j \in \mathcal{J}, \tag{44}$$

respectively. Substituting (42) into both (43) and (44), we can obtain the optimal $\beta_m(J)$, $\forall m \in \mathcal{M}$ and the optimal $\varphi_j(J)$, $\forall j \in \mathcal{J}$, in (23) and (24), respectively.

Appendix B
Proof of Corollary 1

According to (22), if $\ell(J)$ is a non-decreasing function with J, we have

$$\ell(J) - \ell(J-1) \geq 0, \quad \forall J \in \mathcal{K}, \tag{45}$$

which can be rearranged as

$$\begin{aligned}\frac{R_T^w}{R\left(N+K-J+1\right)} &> \left(L - \sum_{m=1}^{M}\frac{R_T^0}{\mathbb{E}^0\left\{R_m\right\}} - \sum_{j=1}^{J-1}\frac{R_T^1}{\mathbb{E}^1\left\{R_j\right\}}\right) + (M+J)\frac{R_T^1}{\mathbb{E}^1\left\{R_J\right\}} \\ &\quad + (M+J)^2 R_T^w\left(\frac{1}{R\left(N+K-J+1\right)} - \frac{1}{R\left(N+K-J\right)}\right) \\ &\triangleq \left(L - \sum_{m=1}^{M}\frac{R_T^0}{\mathbb{E}^0\left\{R_m\right\}} - \sum_{j=1}^{J-1}\frac{R_T^1}{\mathbb{E}^1\left\{R_j\right\}}\right) + \Omega.\end{aligned} \tag{46}$$

Since for the WiFi saturation throughput

$$R\left(N+K-J+1\right) < R\left(N+K-J\right), \tag{47}$$

we have $\Omega > 0$.

On the other hand, from the feasible region of the CP length ℓ in (16), we have

$$\frac{R_T^w}{R\left(N+K-J+1\right)} \leq L - \sum_{m=1}^{M}\frac{R_T^0}{\mathbb{E}^0\left\{R_m\right\}} - \sum_{j=1}^{J-1}\frac{R_T^1}{\mathbb{E}^1\left\{R_j\right\}}, \tag{48}$$

which contradicts with (46). Therefore, $\ell(J) < \ell(J-1)$, $\forall J$.

Appendix C
Proof of Theorem 2

According to (26) and (27), $z^w(J)$ can be expressed with $z^{\mathrm{tot}}(J)$ as

$$z^w(J) = \frac{z^{\mathrm{tot}}(J)}{M+J+1}. \tag{49}$$

Since J^w is the optimal value for $z^w(J)$, we have

$$\frac{1}{M+J^w+1}z^{\mathrm{tot}}\left(J^w\right) > \frac{1}{M+J^t+1}z^{\mathrm{tot}}\left(J^t\right). \tag{50}$$

On the other hand, J^t is the optimal value for $z^{\mathrm{tot}}(J)$, we have $z^{\mathrm{tot}}\left(J^w\right) < z^{\mathrm{tot}}\left(J^t\right)$. Therefore, we can conclude that $J^t > J^w$.

According to Theorem 1 and (26), the objective function of (20a) can be rewritten as

$$z^{\mathrm{NBS}}(J)=\left(\frac{1}{M+J+1}z^{\mathrm{tot}}\left(J\right)\right)^{M+J+1}. \tag{51}$$

Since J^* is the optimal number of LTE-U hybrid users for $z^{\mathrm{NBS}}(J)$, we have

$$\left(\frac{1}{M+J^*+1}z^{\mathrm{tot}}\left(J^*\right)\right)^{M+J^*+1} > \left(\frac{1}{M+J^*+1}z^{\mathrm{tot}}\left(J^*\right)\right)^{M+J^*}\left(\frac{1}{M+J^t+1}z^{\mathrm{tot}}\left(J^t\right)\right), \tag{52}$$

which can be equally written as

$$\frac{1}{M+J^*+1}z^{\mathrm{tot}}\left(J^*\right) > \frac{1}{M+J^t+1}z^{\mathrm{tot}}\left(J^t\right). \tag{53}$$

Similarly, we can conclude that $J^t > J^*$.

To demonstrate the relation between J^* and J^w, we should first rewrite $\widetilde{z}^{\mathrm{NBS}}(J)$ as

$$\widetilde{z}^{\mathrm{NBS}}(J)=(M+J+1)\ln z^{w}(J). \tag{54}$$

Since J^w is the optimal number of LTE-U hybrid users for maximizing $z^w(J)$, we have $z^w(J^*) < z^w(J^w)$. In the ln function, if $Z^w \le 1$, then $\ln(z^w(J^*)) < \ln(z^w(J^w)) < 0$. In this case, if $J^* > J^w$, we have $\widetilde{z}^{\mathrm{NBS}}(J^*) < \widetilde{z}^{\mathrm{NBS}}(J^w)$, which contradicts the fact that J^* maximize the objective function in (25). Thus, $J^* < J^w$. On the other aspect, if $Z^w > 1$, then $0 < \ln(z^w(J^*)) < \ln(z^w(J^w))$. Similarly, we can conclude that $J^* > J^w$. This ends the proof.

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