A Game-Theoretic Approach for Fair Coexistence Between LTE-U and Wi-Fi Systems

Anupam Kumar Bairagi, *Member, IEEE*, Nguyen H. Tran, *Senior Member, IEEE*, Walid Saad, *Senior Member, IEEE*, Zhu Han, *Fellow, IEEE*, and Choong Seon Hong, *Senior Member, IEEE*

***Abstract*—LTE over unlicensed band (LTE-U) has emerged as an effective technique to overcome the challenge of spectrum scarcity. Using LTE-U along with advanced techniques such as carrier aggregation, one can boost the performance of existing cellular networks. However, if not properly managed, the use of LTE-U can potentially degrade the performance of co-existing Wi-Fi access points, which operate over the unlicensed frequency bands. Moreover, most of the existing works consider single operator in their proposals. In this paper, an effective coexistence mechanism between LTE-U and Wi-Fi systems is studied. The goal is to enable the cellular network to use LTE-U with CA to meet the quality-of-service (QoS) needs of its users while protecting Wi-Fi access points (WAPs) for a network with multiple operators. In particular, the problem of LTE-U sum-rate maximization is addressed under user QoS and WAP-LTE-U coexistence constraints. To solve this problem, a cooperative Nash bargaining game (NBG) and a one-sided matching game are proposed. Here, the NBG solves the coexistence issue between LTE-U and Wi-Fi system, while the matching game solves the resources allocation problem in the LTE-U system. These two games repeat until convergence. Simulation results show the quality of the proposed approach over other comparing methods in terms of the per-user achieved rate, percentage of unsatisfied users, and fairness. The result also shows that the proposed approach can better protect the performance of Wi-Fi users, compared to the conventional listen-before-talk scheme.**

***Index Terms*—LTE-U, coexistence, quality-of-service (QoS), Nash bargaining game (NBG), one-sided matching, resource allocation.**

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A. K. Bairagi and C. S. Hong are with the Department of Computer Science and Engineering, Kyung Hee University, Seoul 02447, South Korea (e-mail: anupam@khu.ac.kr; cshong@khu.ac.kr).

N. H. Tran is with the Department of Computer Science and Engineering, Kyung Hee University, Seoul 02447, South Korea, and also with the School of Information Technologies, The University of Sydney, Sydney, NSW 2006, Australia (e-mail: nguyen.tran@sydney.edu.au).

W. Saad is with the Wireless@VT, Bradley Department of Electrical and Computer Engineering, Virginia Tech, Blacksburg, VA 24061 USA, and also with the Department of Computer Science and Engineering, Kyung Hee University, Seoul 02447, South Korea (e-mail: walids@vt.edu).

Z. Han is with the Electrical and Computer Engineering Department, University of Houston, Houston, TX 77004 USA, and also with the Department of Computer Science and Engineering, Kyung Hee University, Seoul 02447, South Korea (e-mail: zhan2@uh.edu).

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I. Introduction

RECENT studies by Cisco [1] have shown that the mobile wireless traffic will continuously increase over in foreseeable future, with mobile video traffic constituting the main chunk of this traffic. As such, cellular network operators (CNOs) and service providers (SPs) must revisit the design of their network, in order to meet the quality-of-service (QoS) requirements of their users. However, despite various advances in cellular industries, the scarcity of the licensed spectrum will remain a key limitation for the cellular networks. Consequently, mobile data offloading from cellular to Wi-Fi has gained recent attention [1]. In fact, some CNOs have already deployed Wi-Fi access points (WAPs) to offload part of their cellular traffic and, in 2016, more than 60% of cellular network traffic was offloaded to the Wi-Fi [1]. But the performance of Wi-Fi technology is not good with huge number of users and it may lead revenue loss for CNOs. Thus, CNOs can overcome the deficiencies of offloading process by implementing LTE-A into unlicensed spectra, known as *LTE-U*. LTE-U improves the RAN capacity of the CNOs at minimal cost. However, the communication range of the unlicensed spectrum is short compared with the licensed one due to the low power regulation and higher frequency. Therefore, small-cell base stations (SBSs) are an appropriate option for LTE-U deployment and CNOs can transform their already deployed SBSs into co-located ones for this purpose; this can be technically assured through carrier aggregation (CA) technology [2]–[4]. LTE-LAA (licensed-assisted-access) is already introduced as part of LTE Release 13 to allow consumers to accommodate licensed and unlicensed carriers under a single LTE network infrastructure [5], [6]. Moreover, inter- and intra-band CA [7], LAA to the ISM band, TV white space and other underutilized resources are required for a full 5G network.

One of the main limitations of LTE-U is that it can cause considerable performance degradation to other existing technologies like Wi-Fi, Bluetooth, ZigBee, etc. Thus, LTE-U SBSs should not cause more interference to a WAP than any other WAP operate over the same unlicensed band. Meanwhile, LTE-U users are also affected by WAPs and other CNOs because of their ad-hoc deployment and utilization of the same unlicensed spectrum. Thus, SBSs for different CNOs and WAPs diminish each others' benefits, including individual benefits, in the unlicensed spectrum. Hence, *coexistence* is the main challenge for LTE-U systems in unlicensed bands.

There are numerous studies [13]–[32] that deal with the coexistence issue between LTE-U and Wi-Fi systems. But very few of them consider effect of multiple CNOs in their coexistence process. Moreover, very few of these studies guaranteed concrete closed-forms for Wi-Fi system protection. Thus, to take advantage of unlicensed spectra in a dense deployment scenario, SBSs need cooperation to find orthogonal resources. For fair coexistence between LTE-U and Wi-Fi systems, a good mechanism for sharing time resources among the contenders is needed, where a *Nash bargaining game* (NBG) [40] is one of the best candidates, which can provide a unique solution. Meanwhile, SBSs have a preference among LTE-U users for allocating the available unlicensed resources in order to maximize utility, and we use a one-sided matching called the *house-allocation model* [37], [38] for this purpose. We propose a coexistence mechanism that can deal with multiple CNOs while demonstrating *fairness* to the Wi-Fi users in the same unlicensed bands. More specifically, the main contributions of this paper are as follows:

- We formulate of an optimization problem to maximize the sum-rate of LTE-U users considering the QoS requirements of the users and coexistence issues with Wi-Fi users.
- We decompose of the problem into two sub-problems: time sharing, and resource allocation. The time sharing problem is solved using a cooperative NBG and the resource allocation problem for each SBS is solved by utilizing a one-sided matching game.
- We find a closed-form solution for time sharing between the LTE-U and Wi-Fi systems, and an algorithm for resource allocation using one-sided matching.
- We justify the quality of the proposed approach with extensive simulations.

The rest of the paper is organized as follows. We provide a literature review in Section II. In Section III, we discuss the system model and problem formulation. The solution to this problem is discussed in Section IV. Performance evaluating criteria and simulation results are discussed in Section V. Finally the paper is concluded in Section VI.

II. Literature Review

To tackle the spectrum scarcity issue, there is a growing consensus among academia and industries of utilizing unlicensed spectrum in LTE network. There are noteworthy studies [9]–[11] that assess the performance of LTE-U in the presence of WAPs. In [9], the authors presented analytical results of LTE-U and WLAN by applying a simple fractional unlicensed bandwidth sharing technique. The authors in [10] noticed that WiFi users' performance is degraded by about 70% to 100% depending on if it is sparse or dense deployment in the LTE-U system without inter-system coordination. A similar finding is also presented in [11]. There are some potential proposals to mitigate the interference between LTE-U and WiFi networks from industrial fields. Qualcomm proposed dynamic channel selection (DCS), carrier-sensing adaptive transmission (CSAT), and opportunistic SDL (OSDL) for the fair coexistence between LTE-U and Wi-Fi systems in [12].

TABLE I
Summary of the Related Works

Ref.	BS/SBSs	Method	Limitation
[13]	Single	Fraction of time	Inter-operator interference and closed-form solution of time
[14]	Multiple	Fraction of time	Performance of LTE-U users
[15]	Multiple	Fraction of time	Heuristic algorithm for resource allocation
[16]	Multiple	Fraction of time	Sharing of time among multiple SBSs, Wi-Fi protection
[17]	Single	LBT	Inter-operator interference, performance in dense environment
[18]	Multiple	LBT	Performance in dense scenario
[19]	Multiple	Duty cycle adjustment	Number of states, no performance guarantee
[21]	Multiple	Contention-based protocol	Performance of such approach may suffer in dense scenario
[22]	Single	Energy threshold	Inter-operator interference, externalities in preference list
[23]	Single	Energy threshold	Inter-operator interference, sharing all the information of WAPs
[24]	Single	Transfer of Wi-Fi users	Inter-operator interference, integration of Wi-Fi users with LTE system
[25]	Single	Contention-free period	Inter-operator interference, centralized controller for HAP and WAPs
[26]	Multiple	Interference penalty	WAPs need to share all the information with CNOs, overhead among CNOs and users
[27]	Single	Offloading to WAP	Inter-operator interference, performance is unsatisfactory in dense environment
[28]	Single	Free channel	Inter-operator interference, fully centralized, no fairness
[29]	Single	NFV by centralized controller	Inter-operator interference, centralized controller
[30]	Multiple	Time division and SDN controller	Overhead of centralized controller, sharing of every information
[31]	Single	Zero-forcing transmit beamforming	Inter-operator interference, CSI of Wi-Fi users
[32]	Single	Fraction of time	Inter-operator interference, no closed-form solution for sharing fraction of time

For sharing the unlicensed spectrum between the LTE network and WiFi systems, a time-domain resource splitting approach is used in [13]. The authors formulated a resource allocation problem of an LTE system by decoupling the uplink-downlink and also licensed-unlicensed band with the help of echo state network. The authors in both [14] and [15] introduced efficient coexistence strategies for inter-operator interference management based on a collaborative Nash bargaining game (NBG). To this end, the work in [14] used a bankruptcy game for user level resource allocation, whereas a heuristic algorithm is adopted in [15] for the same purpose. In both cases, the proposed approaches are shown to outperform LBT, in terms of maintaining a desirable throughput for WiFi. The authors of [16] proposed a spectrum sharing scheme between LTE-U and WiFi networks based on cognitive coexistence.

An listen-before-talk (LBT) based mechanism with a distributed coordination function (DCF) protocol and adaptive backoff window size has been proposed for the fair coexistence between the LTE-U system and WAPs in [17]. Authors in [18] also use LBT mechanism in a multi-operators scenario. They introduce deep reinforcement learning framework in their model. In [19], the authors addressed the problem of coexistence between LTE-U and Wi-Fi by employing Q-learning for optimized duty cycle. However, the results in [19] show that the WiFi throughput will be significantly degraded compared to LBT and CSAT. The authors in [21] introduced proactive resource allocation for LTE-U using a novel deep reinforcement learning algorithm that uses long short term memory (RL-LSTM). The proposed solution in [21] jointly decides channel selection, CA, and fractional spectrum access for each SBS, while assuring long-term airtime fairness for WLAN.

Beyond the aforementioned methods, there has been some recent works for optimizing the coexistence between LTE-U and Wi-Fi systems using matching theory. The authors in [22] study CA for the licensed and unlicensed spectra by deploying a dual-mode LTE MBS by modeling the problem via a matching game, namely student-project allocation. The authors modeled the interaction between LTE and Wi-Fi users as a stable marriage (SM) game in [23].

A bargaining game framework is used to solve the interactions between LTE-U and Wi-Fi networks in the works [24], [25]. The authors in [24] created a win-win situation for both LTE-U and WiFi networks by transferring some of the Wi-Fi users to the LTE-U system with the help of Nash bargaining solution (NBS). In [25], the authors introduced a hyper access point (HAP), which provides a contention-free period to LTE-U users and a contention period for Wi-Fi users to promote coexistence.

In [26], the authors developed a multi-operator multi-user Stackelberg game for investigating the interplay between CNOs and UEs in the unlicensed spectrum. For protecting WAPs, each CNO sets an interference penalty price for each UE in this game. To mitigate the interference between LTE-LAA and Wi-Fi, the authors in [27] proposed a coalition game-based approach by offloading part of the data traffic from LTE-LAA to a nearby WAP with the help of almost-blank-subframe (ABS). The authors in [28] proposed a coexistence mechanism between LTE-U and Wi-Fi by formulating it as an AP selection problem using a centralized coalition formation game. The proposed approach in [28] gives high priority to the SBS for accessing the unlicensed channel while WAPs can only access the channel when it is free. However, this work did not analyze fairness measures related to LTE-U-WiFi coexistence.

The works in [29], [30] studied cooperative coexistence between LTE-U and Wi-Fi systems in a fully centralized manner. The authors implode the management tasks of both LTE-U and Wi-Fi networks with the help of network function virtualization (NFV) in [29]. To ameliorate spectrum utilization and expedite coexistence among different networks, the authors used the software-defined networking (SDN) architecture to support logical control over the system in [30].

A general framework for fair coexistence between LTE and WiFi systems is proposed in [31] by leveraging multi-antenna transmit beamforming technique for spatial reuse. The model of [31] allocates optimal power to balance the throughput of the two systems. However, the solution proposed in [31] requires gathering the CSI of all WiFi users which is practically challenging. The work in [32] proposed a joint channel selection and frame scheduling optimization framework for LTE systems while considering fairness with WLAN. However, the proposed approach in [32] presents no solution for sharing time between the two systems in the unlicensed spectrum. Though the coexistence of LTE-A and narrowband Internet of Things (NB-IoT) [34] is important for 5G, the work in [34] does not address the problem of LTE-U and WiFi coexistence.

Hence, most of the works [13], [17], [22]–[25], [27]–[29], [31], [32] in the literature do not consider the mutual interference between operators, for effective cellular-WiFi coexistence in the unlicensed band. Meanwhile, the handful of works [16], [18], [19], [26], [30] that consider this inter-operator interference have their own limitations. For instance, the work in [16] does not provide any solution for time-sharing among multiple SBSs, whereas the works in [18] and [19] exhibit a low performance in dense deployment scenarios due to their reliance on LBT. Moreover, the solution proposed in [26] and [30] require a centralized controller that collects information on every WiFi and LTE user in the network which yields a large overhead. Meanwhile, existing works that study time-sharing mechanisms for LTE-U, such as in [13], [16], and [32] do not provide any optimal solution for coexistence. Hence, there is a need for a new approach to ensure a fair coexistence between LTE-U and WiFi systems considering multiple SBSs belonging to different operators, while requiring minimum information exchange. As such, in this work, all these challenges are addressed. If LTE-U and Wi-Fi use a different unlicensed channel, then there is no obstacle. But given that the number of non-overlapping unlicensed channels are limited, there must be a situation when LTE-U and Wi-Fi need to use the same unlicensed channel, which leads the coexistence problem interesting and challenging.

III. System Model and Problem Formulation

Consider a cellular network having a set $\mathcal{S}$ of S dual-mode (which can act both in the licensed and unlicensed spectrum) LTE-A SBSs operated by different operators and a set $\mathcal{W}$ of W non-overlapping WAPs as shown in Fig. 1. Each SBS $i \in \mathcal{S}$ can serve, in the downlink, an user set $\mathcal{U}_i$, using a set of orthogonal licensed subchannels $\mathcal{C}_l^i$ of uniform bandwidth B_l. WAP $w \in \mathcal{W}$ has a set $\mathcal{V}_w$ of V_w active users. Both SBSs and WAPs operate in the same unlicensed band. Thus, an LTE-U user can be affected by $S-1$ SBSs and one WAP as $\mathcal{W}$ are non-overlapping, whereas a Wi-Fi user will experience interference by S SBSs. Each SBS divides one traditional WiFi band of 20 MHz into a set

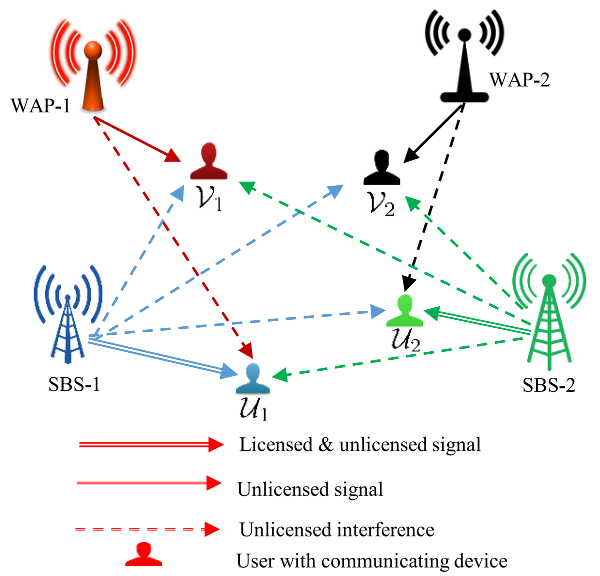

Fig. 1. Illustration of the system model.

of finite subchannels $\mathcal{C}_u$ (e.g., containing 100 subchannels) with uniform bandwidth B_u, e.g., 180 kHz, for efficient management of resource. For reliable transmission of control signals from the SBS to the user, each SBS allocates at least one licensed subchannel to its active users. Actually, LTE-U can be deployed using either a supplemental downlink (SDL) mode or using time-division duplexing (TDD) mode. The unlicensed spectrum is used only for the downlink in SDL, whereas in TDD, the unlicensed spectrum can be used for both uplink and downlink. Here, we consider LTE-U as SDL which was supported by 3GPP Release 13 as LAA [5], [6]. 3GPP has already introduced an uplink access scheme for LTE-U, namely enhanced LAA (eLAA) in its Release 14 [8] and hence, carrier aggregation for both uplink and downlink is made possible by using either licensed TDD or licensed frequency division duplexing (FDD). To this end, the proposed approach can be extended to handle the uplink, by adopting a TDD operation mode instead of SDL. All the SBSs work in the SDL mode using CA. The main parameters used in this work is represented in Table II.

TABLE II
SUMMARY OF NOTATIONS

Symbol	Meaning
$\mathcal{S}$	Set of SBSs with S elements
$\mathcal{W}$	Set of non-overlapping WAPs with W elements
$\mathcal{U}_i$	Set of users associated with SBS i
$\mathcal{V}_w$	Set of V_w active users associated with WAP w
$\mathcal{C}_l^i$	Set of licensed subchannels of SBS i
$\mathcal{C}_u$	Set of subchannels of a traditional 20 MHz WiFi band
$\mathcal{C}_u^i$	Set of unlicensed subchannels that SBS i gets after division of $\mathcal{C}_u$
B_l	Bandwidth of each licensed subchannel
B_u	Bandwidth of each unlicensed subchannel
P_i^l	Transmission power of SBS i for each user in licensed spectrum
P_i^u	Transmission power of SBS i for each user in unlicensed spectrum
$\boldsymbol{x}_i$	Resource allocation vector for SBS i in licensed spectrum
$\boldsymbol{y}_i$	Resource allocation vector for SBS i in unlicensed spectrum
$\|h_{i,j}\|^2$	Channel gain between AP i and receiver j
$d_{i,j}$	Distance between AP i and receiver j
G	Constant power gain factor
α	Path-loss exponent
h_0	Rayleigh fading
$I_{\mathcal{S}\setminus\{i\}}$	Interference from $\mathcal{S}$ to any user of i in any unlicensed subchannel
$R_{i,j}^{l,k}$	Achieved rate of user j associated with SBS i in the licensed subchannel k
$R_{i,j}^{u,k'}$	Achieved rate of user j associated with SBS i in the unlicensed subchannel k'
$R_{i,j}^l$	Achieved rate of user j associated with SBS i in licensed spectrum
$R_{i,j}^u$	Achieved rate of user j associated with SBS i in unlicensed spectrum
$R_{i,j}$	Achieved rate of user j associated with SBS i
$R_{w,v}^{\max}$	Average rate of user v associated with WAP w when WAP is accessing the channel
$R_{w,v}^{\min}$	Average rate of user v associated with WAP w when SBSs act like WAPs
$Q_{i,j}$	QoS requirement of user j associated with SBS i
τ	Fraction of time that SBSs share with WAPs
AQR	Additional QoS requirements vector of the SBSs

A. Data Rate of LTE-U User

In our model, each SBS uses an orthogonal frequency division multiple access (OFDMA) technique to allocate resources among its users, there is no intra-operator interference in the licensed spectrum. When SBS $i \in \mathcal{S}$ allocates the licensed subchannel $k \in \mathcal{C}_l^i$ to the user $j \in \mathcal{U}_i$, the achieved rate of that user is as follows:

$$R_{i,j}^{l,k} = B_l \log_2 \left(1 + \frac{x_{i,j}^k P_i^l |h_{i,j}|^2}{\sigma^2} \right), \quad (1)$$

where $x_{i,j}^k$ indicates the allocation of the licensed subchannel $k \in \mathcal{C}_l^i$ by SBS $i \in \mathcal{S}$ to user $j \in \mathcal{U}_i$ with $x_{i,j}^k = 1$ when SBS $i \in \mathcal{S}$ allocates the subchannel to user and $x_{i,j}^k = 0$, otherwise. P_i^l is the transmission power of SBS i for each user, and we consider equal transmit power for simplicity. $|h_{i,j}|^2$ is the channel gain from SBS i to user j considering a free space propagation path-loss model with Rayleigh fading and $|h_{i,j}|^2 = G d_{i,j}^{-\alpha} |h_0|^2$, where G indicates constant power gain factor introduced by the amplifier and antenna, $d_{i,j}$ is the distance between i and j, α is the path-loss exponent and $h_0 \sim \mathcal{CN}(0,1)$ represents Rayleigh fading. The thermal noise has an independent Gaussian distribution with zero mean and variance σ^2.

An LTE-A system can employ CA to provide a better rate to its users for maintaining the QoS if SBS has sufficient unused licensed subchannels. When SBS $i \in \mathcal{S}$ allocates more than one subchannel to user $j \in \mathcal{U}_i$, then the achieved rate of that user over the licensed subchannels will be:

$$R^l_{i,j}(\boldsymbol{x}_i) = \sum_{k \in \mathcal{C}^i_l} x^k_{i,j} R^{l,k}_{i,j}. \quad (2)$$

If $R^l_{i,j}(\boldsymbol{x}_i)$ is sufficiently large to meet the QoS of user j, then the network will not need to use the unlicensed spectrum for that user. However, whenever the rate over the licensed spectrum band is not able to provide the needed QoS, the associated SBS will have to allocate unlicensed subchannel(s) to those users. In that case, the rate obtained by LTE-U user $j \in \mathcal{U}_i$ over the unlicensed subchannel $k' \in \mathcal{C}_u$ is as follows:

$$R^{u,k'}_{i,j} = B_u \log_2 \left(1 + \frac{y^{k'}_{i,j} P^u_i |h_{i,j}|^2}{I_{\mathcal{S}\setminus i} + \sigma^2} \right), \quad (3)$$

where $y^{k'}_{i,j} = 1$ when SBS $i \in \mathcal{S}$ allocates the unlicensed subchannel to the specified user j and $y^{k'}_{i,j} = 0$, otherwise. P^u_i is the transmission power for a cellular user of SBS i in an unlicensed spectrum. $|h_{i,j}|^2$ is the channel gain between SBS i and user j in the unlicensed subchannel, and $I_{\mathcal{S}\setminus i} = \sum_{s \in \mathcal{S}, s \neq i} \sum_{n \in \mathcal{U}_s} y^{k'}_{s,n} P^u_s |h_{s,j}|^2$ is the interference perceived by LTE-U user $j \in \mathcal{U}_i$ from other SBSs in the same unlicensed subchannel $k' \in \mathcal{C}_u$. We ignore the interference produced from WAP because of its' negligible impact on LTE-U user [10].

However, due to the un-coordinated SBSs deployment of different operators, $I_{\mathcal{S}\setminus i} >> P^u_i |h_{i,j}|^2$, and so $R^{u,k'}_{i,j}$ will be negligible. Thus, to take advantage of this unlicensed band, SBSs can use a proportional fairness [35] scheme to divide the unlicensed resources in an orthogonal fashion among themselves. For this, each SBS $i \in \mathcal{S}$ sends its additional QoS requirement ($AQR_i = \sum_{j \in \mathcal{U}_i} \max(Q_{i,j} - R^l_{i,j}, 0)$) to an operator known as an arbitrator. Following the fairness strategy, the arbitrator distributes the unlicensed resources among SBSs with the help of Algorithm 1. Assume the unlicensed subchannels are distributed among the SBSs as $\mathcal{C}_u = \mathcal{C}^1_u \cup \mathcal{C}^2_u \cup \ldots \cup \mathcal{C}^S_u$, where $\mathcal{C}^i_u \cap \mathcal{C}^{i'}_u = \emptyset, \forall i, i' \in \mathcal{S}$. In this way SBSs can avoid the inter-SBSs' interference $I_{\mathcal{S}\setminus i}$. Thus from (3), the data rate obtained by LTE-U user $j \in \mathcal{U}_i$ in the unlicensed subchannel $k' \in \mathcal{C}^i_u$ is as follows:

$$R^{u,k'}_{i,j} = B_u \log_2 \left(1 + \frac{y^{k'}_{i,j} P^u_i |h_{i,j}|^2}{\sigma^2} \right). \quad (4)$$

Similarly, if SBS $i \in \mathcal{S}$ allocates multiple unlicensed subchannels to user $j \in \mathcal{U}_i$, then the achieved rate of that user in this spectrum is as follows:

$$R^u_{i,j}(\boldsymbol{y}_i) = \sum_{k' \in \mathcal{C}^i_u} y^{k'}_{i,j} R^{u,k'}_{i,j}. \quad (5)$$

Algorithm 1: Division of Unlicensed Resources among SBSs.

```
Input: S, C_u, AQR
Output: C_u^i, ∀i ∈ S
Initialization: C_u^i = ∅, ∀i ∈ S
for each i ∈ S do
    K = (AQR_i / Σ_{i'∈S} AQR_{i'}) · |C_u|
    for s = 1 to K do
        C_u^i = C_u^i ∪ {s}
    end for
end for
Arbitrator sends C_u^i to each i ∈ S
```

Accordingly, the total achievable rate of user $j \in \mathcal{U}_i$ in both the licensed and unlicensed spectrum is as follows:

$$R_{i,j}(\boldsymbol{x}_i, \boldsymbol{y}_i) = R^l_{i,j}(\boldsymbol{x}_i) + R^u_{i,j}(\boldsymbol{y}_i). \quad (6)$$

Here, we are considering a set of QoS unsatisfied users $\mathcal{U}'_i \subseteq \mathcal{U}_i$ who need assistance from the unlicensed spectrum. Each user $j \in \mathcal{U}'_i$ possesses at least one licensed subchannel for uninterrupted exchange of control information.

B. Data Rate of Wi-Fi Users

When the unlicensed channel is fully utilized by a WAP, then it can provide the maximum rate to its users. In this case, average throughput of each user $v \in \mathcal{V}_w$ associated with WAP $w \in \mathcal{W}$ can be represented as follows:

$$R^{\max}_{w,v} = \frac{R_w}{V_w}, \quad (7)$$

where R_w is the overall downlink throughput of the $w \in \mathcal{W}$. Now, when all SBSs use the same unlicensed band as the WAPs, the performance of WAPs will be affected. If we consider that each SBS in the conflicting region acts just like a WAP, then the normalized throughput for each WAP $w \in \mathcal{W}$ according to [36] is as follows:

$$R^{\min}_w = \frac{P_{tr} P_s E[P] (S+1)^{-1}}{(1 - P_{tr}) T_\sigma + P_{tr} P_s T_s + P_{tr} (1 - P_s) T_c}. \quad (8)$$

where $P_{tr} = 1 - (1 - \tau)^{S+1}$ is the transmission probability of at least one SBS or WAP in a time slot with τ denoting the stationary transmission probability of AP. P_s is the successful transmission on the channel with $P_s = \frac{(S+1)\tau(1-\tau)^S}{P_{tr}}$ and $E[P]$ represents the average packet size. T_σ is the duration of an empty slot time, T_s presents the time duration of a successful transmission, and T_c illustrates the average time of a collision. The average downlink rate achieved by each user $v \in \mathcal{V}_w$ of WAP $w \in \mathcal{W}$ is represented as follows:

$$R^{\min}_{w,v} = \frac{R^{\min}_w}{V_w}. \quad (9)$$

When SBSs use the same unlicensed band, they have to provide channel access opportunity to WAPs for the sake of fair coexistence. By that way, WAPs can provide an good throughput $[R^{\min}_{w,v}, R^{\max}_{w,v}]$ to its users.

C. Problem Formulation

We observe that $R_{w,v}^{\max}$ is achievable when only WAPs access the unlicensed channel. But if WAPs and SBSs are deployed in the same conflicting area and use the same unlicensed band, then Wi-Fi users will get almost no access in the channel and have significantly low data rate. Thus, for the fair coexistence of Wi-Fi and LTE-U systems, they need to share the time slots such that WAPs can maintain minimum data rates for its users and SBSs can at least improve some of the users' QoS. As the LTE-U system manages the physical resources in a centralized manner rather than the DCF of WAPs, SBSs need to decide appropriate portions of time to achieve minimum throughput for each Wi-Fi user. When SBSs give up a fraction of time slot $\tau \in [0,1]$ of the unlicensed spectrum for WAPs, the achievable rates of Wi-Fi and LTE-U users (consider $\boldsymbol{x}_i$ is fixed for current time slot) are shown, respectively, as follows:

$$R_{w,v}(\tau) = R_{w,v}^{\max} \cdot \tau, \forall v \in \mathcal{V}_w. \tag{10}$$

$$R_{i,j}(\tau, \boldsymbol{x}_i, \boldsymbol{y}_i) = R_{i,j}^{l}(\boldsymbol{x}_i) + (1-\tau) \cdot R_{i,j}^{u}(\boldsymbol{y}_i). \tag{11}$$

Thus, the sum-rate of SBS $i \in \mathcal{S}$ when it shares τ time slot with WAPs is as follows:

$$R_i(\tau, \boldsymbol{x}_i, \boldsymbol{y}_i) = \sum_{j \in \mathcal{U}_i} R_{i,j}(\tau, \boldsymbol{x}_i, \boldsymbol{y}_i). \tag{12}$$

Our problem is now confined by the unlicensed spectrum to maximize the sum-rate of the SBS after sharing a τ-fraction of time with the WAPs while maintaining QoS for most of the users. For this, we need to develop an efficient spectrum allocation scheme for each SBS i to maximize the utility function $U_i(\tau, \boldsymbol{y}_i) = \sum_{j \in \mathcal{U}_i'} \log((1-\tau) \cdot R_{i,j}^{u}(\boldsymbol{y}_i))$ in the unlicensed spectrum.

$$\begin{aligned} \max_{\tau, \boldsymbol{y}_i} \quad & U_i(\tau, \boldsymbol{y}_i), \forall i \in \mathcal{S} \\ \text{s.t.} \quad & C_1 : \sum_{j \in \mathcal{U}_i'} y_{i,j}^{k'} \le 1, \forall k' \in \mathcal{C}_u^i \\ & C_2 : \sum_{j \in \mathcal{U}_i'} \sum_{k' \in \mathcal{C}_u^i} y_{i,j}^{k'} \le |\mathcal{C}_u^i| \\ & C_3 : R_{i,j}(\tau, \boldsymbol{x}_i, \boldsymbol{y}_i) \ge Q_{i,j}, \forall j \in \mathcal{U}_i' \\ & C_4 : y_{i,j}^{k'} \in \{0,1\}, \forall k' \in \mathcal{C}_u^i, \forall j \in \mathcal{U}_i' \\ & C_5 : R_{w,v}^{\min} \le R_{w,v}(\tau) \le R_{w,v}^{\max}, \forall v \in \mathcal{V}_w \\ & C_6 : 0 \le \tau \le 1. \end{aligned} \tag{13}$$

Here, the constraint C_1 indicates that one unlicensed subchannel can be utilized by at most one LTE-U user. The limitations of total resources in this spectrum are represented by constraint C_2 for each SBS. The QoS requirement of LTE-U users are mitigated by constraint C_3. Every element of the allocation vector $\boldsymbol{y}_i$ will be either 0 or 1 as shown by constraint C_4. Wi-Fi users are protected by constraints C_5 and C_6. The optimization problem in (13) is a Mixed Integer Non-Linear Programming (MINLP) problem, which is NP-hard due to its combinatorial property.

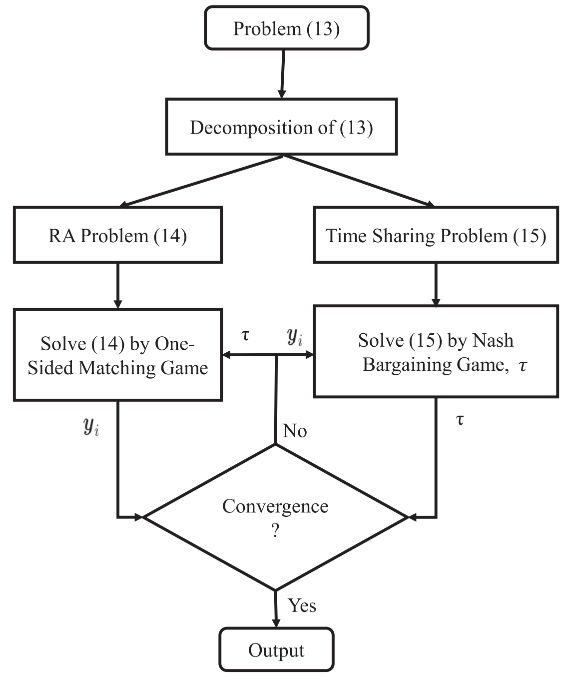

Fig. 2. Solution approach to the problem (13).

IV. Nash Bargaining and Matching Game based Solution Approach

Now we want to decompose the problem in (13) into two sub-problems so that individual ones can be solved with appropriate techniques. First, with fixed τ, unlicensed resources should be allocated to the users so that the system throughput can be maximized while satisfying some constraints as follows:

$$\begin{aligned} \max_{\boldsymbol{y}_i} \quad & U_i(\tau, \boldsymbol{y}_i), \forall i \in \mathcal{S} \\ \text{s.t.} \quad & C_1, C_2, C_3, \text{and } C_4. \end{aligned} \tag{14}$$

Secondly, with fixed resource allocation (which we get from (14)), the time sharing problem between SBSs and WAPs can be represented as follows:

$$\begin{aligned} \max_{\tau} \quad & U_i(\tau, \boldsymbol{y}_i), \forall i \in \mathcal{S} \\ \text{s.t.} \quad & C_5, \text{and } C_6. \end{aligned} \tag{15}$$

Sub-problems (14) and (15) have the same goal with different constraints and are connected through the parameters τ and $\boldsymbol{y}_i$. The solution ($\boldsymbol{y}_i$) of (14) is used to solve (15), while the solution (τ) of (15) is used to solve (14) repeatedly until convergence. This solution approach is shown in Fig. 2. Now, we solve the problems (14) and (15) with the help of a *one-sided matching game* and *NBG*, which gives an approximation and unique optimal solution, respectively. The details of these two approaches are in the following section.

A. Solution of Problem (14)

The problem shown in (14) is still NP-hard and cannot be solved in real time. So, to solve this resource allocation problem for each SBS $i \in \mathcal{S}$, we use the framework of the *house* *allocation problem* (HAP) [37], [38]. HAP provides a suboptimal solution with less complexity. The house allocation problem is a one-sided matching represented by a tuple $(\mathcal{A}, \mathcal{H}, \mathcal{P})$, where $\mathcal{A}$ is the set of agents, $\mathcal{H}$ is comprised of a set of houses, and $\mathcal{P}$ represents the preferences of agents over the houses. In our context of SBS $i \in \mathcal{S}$, unlicensed subchannels $\mathcal{C}_u^i$ are the agents, the LTE-U users in set $\mathcal{U}_i^{'}$ correspond to the houses, and $\mathcal{C}_u^i$ have preferences over $\mathcal{U}_i^{'}$. The SBSs are assumed to have full knowledge on their users. In this matching model, if SBS $i \in \mathcal{S}$ allocates subchannel $k \in \mathcal{C}_u^i$ to LTE-U user $j \in \mathcal{U}_i^{'}$, then LTE-U user j is said to be matched with subchannel k and form a matching pair (j, k).

A matching is an assignment of subchannels in $\mathcal{C}_u^i$ to LTE-U users in $\mathcal{U}_i^{'}$, which can be defined as follows:

Definition 1: A matching Ω_i for each $i \in \mathcal{S}$ between $\mathcal{C}_u^i$ and $\mathcal{U}_i^{'}$ is a mapping from the set $\mathcal{C}_u^i \cup \mathcal{U}_i^{'}$ to the set of all subsets of $\mathcal{C}_u^i \cup \mathcal{U}_i^{'}$ such that for every $k \in \mathcal{C}_u^i$ and every $j \in \mathcal{U}_i^{'}$: i) $\Omega_i(k) \in \mathcal{U}_i^{'}$ and $\Omega_i(j) \in \mathcal{C}_u^i$, ii) $|\Omega_i(k)| \leq 1$, iii) $|\Omega_i(j)| \leq q_j$, where q_j is the minimum number of subchannels to meet the QoS of user j, and (iv) $k \in \Omega_i(j)$ if and only if $j \in \Omega_i(k)$.

The value of q_j is not predefined for each $j \in \mathcal{U}_i^{'}$, rather SBS determines it dynamically based on the QoS requirement of the requested application by the user. Definition 1 states that an unlicensed subchannel k can only be matched with one LTE-U user from $\mathcal{U}_i^{'}$ while one LTE-U user j can be matched with multiple unlicensed subchannels of $\mathcal{C}_u^i$. For allocating unlicensed subchannels $\mathcal{C}_u^i$ to the users $\mathcal{U}_i^{'}$, each subchannel requires specifying its preferences over the users depending on its utility function. The utility of subchannel k while it is utilized by user j is as follows:

$$U_k(j) = R_{i,j}^{u,k}, \forall j \in \mathcal{U}_i^{'}. \tag{16}$$

Based on the utility function, each subchannel $k \in \mathcal{C}_u^i$ can define its preference relation $\mathcal{L}_k$ over the set of users $\mathcal{U}_i^{'}$, such that for any two users $j, j' \in \mathcal{U}_i^{'}, j \neq j'$ and two matching $\Omega_i, \Omega_i^{'}$, $j \in \Omega_i(k), j' \in \Omega_i^{'}(k)$:

$$(j, \Omega_i) \succ_k (j', \Omega_i^{'}) \Leftrightarrow U_k(j, \Omega_i) \succ_k U_k(j', \Omega_i^{'}). \tag{17}$$

So, each subchannel $k \in \mathcal{C}_u^i$ builds its preference list $\mathcal{L}_k$ by sorting the utilities that it gets from (16) in descending order. In the original house allocation problem, one agent is allocated to only one house but in our problem, multiple subchannels can be allocated to one user. Therefore, our goal is to find a matching outcome that is both Pareto optimal and resides in the core. Both of these are defined as follows:

Definition 2: A matching Ω_i is Pareto optimal if there is no other matching $\Omega_i^{'}$ where at least one of the members of $\mathcal{C}_u^i$ can improve its utility without affecting the utilities of others.

Definition 3: A matching Ω_i is in the core of the one-sided matching if there is no coalition $\mathcal{C}_u^{i'} \subseteq \mathcal{C}_u^i$ and a matching $\Omega_i^{'}$ such that: (i) $\Omega_i^{'}(k) \in \{j \in \mathcal{U}_i^{'} : j = \Omega_i(k^{'}), \exists k^{'} \in \mathcal{C}_{u'}^i\}, \forall k \in \mathcal{C}_{u'}^i$, ii) $\Omega_i^{'}(k) \succeq_k \Omega_i(k), \forall k \in \mathcal{C}_u^{i'}$, and iii) $\Omega_i^{'}(k) \succ_k \Omega_i(k), \exists k \in \mathcal{C}_u^{i'}$ holds.

Based on the preference $\mathcal{L}_k, \forall k \in \mathcal{C}_u^i$, a one-sided matching-based resource allocation process for each SBS $i \in \mathcal{S}$ is shown in Algorithm 2. The output Ω_i of Algorithm 2 can be transformed to a feasible allocation vector $\boldsymbol{y}_i$ of problem (14) for each SBS $i \in \mathcal{S}$.

Algorithm 2: One-Sided Matching-Based RA for SBS i.

1: **Input**: $\tau, \mathcal{U}_i^{'}, \mathcal{C}_u^i, \mathbf{Q}_i, \mathbf{R}_i^l$
2: **Output**: Ω_i
3: **for** each $k \in \mathcal{C}_u^i$ **do**
4:   Makes preference list $\mathcal{L}_k$ over $\mathcal{U}_i^{'}$
5: **end for**
6: Each user $j \in \mathcal{U}_i^{'}$ informs its demand (QoS requirement of current application) to the SBS i
7: **repeat**
8:   SBS i takes first elements of $\mathcal{L}_k, \forall k \in \mathcal{C}_u^i$ and finds the set of sub-channels whose most preferred user is $j, \forall j \in \mathcal{U}_i^{'}$ denoted as $\mathcal{M}_j$
9:   **for** each $j \in \mathcal{U}_i^{'}$ **do**
10:     SBS sorts $\mathcal{M}_j$ according to their utility for user j in descending order and denote it as $\mathcal{M}_j^{sort}$
11:     **if** $\sum_{k \in \mathcal{M}_j^{sort}} (1 - \tau) \cdot R_{i,j}^{u,k} < Q_{i,j} - R_{i,j}^l$ **then**
12:       Holds $\forall k \in \mathcal{M}_j^{sort}$ for j
13:     **else**
14:       Keep $\min |\mathcal{M}_j^{sort'}|$ for j such that $\mathcal{M}_j^{sort'} \subseteq \mathcal{M}_j^{sort}$ and $\sum_{k \in \mathcal{M}_j^{sort'}} (1 - \tau) \cdot R_{i,j}^{u,k} \geq Q_{i,j} - R_{i,j}^l$ and remove others from $\mathcal{M}_j^{sort}$
15:       $\mathcal{U}_i^{'} \leftarrow \mathcal{U}_i^{'} \setminus \{j\}$
16:       Remove j from $\mathcal{L}_k, \forall k \in \mathcal{C}_u^i$
17:     **end if**
18:     $\mathcal{C}_u^i \leftarrow \mathcal{C}_u^i \setminus \mathcal{M}_j^{sort}$
19:   **end for**
20: **until** $\mathcal{U}_i^{'} = \emptyset$ or $\mathcal{C}_u^i = \emptyset$

Theorem 1: Algorithm 2 produces a Pareto optimal matching $\Omega_i, \forall i \in \mathcal{S}$ for a given τ.

Proof: We prove this theorem using contraction which is also used to prove Pareto optimality in the house allocation problem [39]. We assume that Algorithm 2 generates a matching Ω_i that is not Pareto optimal. That means there can be another matching $\Omega_i^{'}$ in which at least one subchannel $k \in \mathcal{C}_u^i$ can improve its utility without affecting the utilities of others. In such a situation, let $j = \Omega_i(k)$ and $j^{'} = \Omega_i^{'}(k)$. As $j^{'} \succ_k j$, so either k resides in the lower order of $\mathcal{M}_{j^{'}}^{sort}$, which is not necessary to meet the remaining demand $(Q_{i,j'} - R_{i,j'}^l)$ and has been removed (line 14), or $j^{'}$ is removed from $\mathcal{L}_k$ (line 16) due to an other $k^{'} \in \mathcal{C}_u^i, k^{'} \neq k$, who matched with $j^{'}$ before. Thus, $k \neq \Omega_i^{'}(j^{'})$ and hence, Ω_i is Pareto optimal. ■

Theorem 2: Algorithm 2 produces a matching $\Omega_i, \forall i \in \mathcal{S}$ which is in the core for a given τ.

Proof: We prove this theorem using contradiction. We assume that Algorithm 2 provides a matching Ω_i that is not in the core. That means there is at least two subchannels $\{k, k^{'}\} \subseteq \mathcal{C}_u^i$ who want to exchange their current matching partners to form new matching $\Omega_i^{'}$. In Ω_i, let $j = \Omega_i(k)$ and $j^{'} = \Omega_i(k^{'})$. Now from definition 2, $j^{'} \succ_k j$ and $j \succ_{k'} j^{'}$. That means either (i) k stays in the lower order of $\mathcal{M}_{j^{'}}^{sort}$ and is removed (line 14) as it is unnecessary to meet $(Q_{i,j'} - R^l_{i,j'})$, or (ii) j' is removed from $\mathcal{L}_k$ (line 16) due to another $k' \in \mathcal{C}^i_u, k' \neq k$, and k' is matched with j' before. Similarly, either (i) k' remains in the lower order of $\mathcal{M}^{sort}_j$, is unnecessary to meet $(Q_{i,j} - R^l_{i,j})$ and has been removed (line 14), or (ii) j has been removed from $\mathcal{L}_{k'}$ (line 16) due to another $k \in \mathcal{C}^i_u, k \neq k'$ that is already matched with j. Thus, neither k nor k' can exchange their current partners to obtain better utilities. It indicates that there exists no matching Ω'_i and hence, Ω_i is in the core. ■

B. Nash Bargaining Game-Based Solution of Problem (15)

From (15), if we want to maximize $U_i(\tau, \boldsymbol{y}_i)$ for each SBS $i \in \mathcal{S}$, this can be detrimental to the performance of WAPs due to the aggressive access mechanism of the LTE-U system. In this subsection, we will propose a win-win strategy for both SBSs and WAPs based on the NBG. Specifically, we will find an effective unlicensed time slot allocation scheme to balance the benefit between SBSs and WAPs.

Now redefine the problem of (15) to balance the benefits of both SBSs and WAP as follows:

$$\begin{aligned} \max_{\tau} \quad & U_S(\tau, \boldsymbol{y}) U_w(\tau) \\ \text{s.t.} \quad & R^{\min}_{w,v} \le R_{w,v}(\tau) \le R^{\max}_{w,v}, \forall v \in \mathcal{V}_w, \\ & \tau_0 \le \tau \le 1. \end{aligned} \tag{18}$$

where $U_S(\tau, \boldsymbol{y}) = \sum_{i \in \mathcal{S}} U_i(\tau, \boldsymbol{y}_i)$, $U_w(\tau) = V_w \cdot R_{w,v}(\tau)$ and τ_0 is the time necessary for maintaining the $R^{\min}_{w,v}$ rate for each Wi-Fi user $v \in \mathcal{V}_w$ when only WAPs are using the channel. This is a multi-objective problem, so we can use the bargaining game to distribute time resources (τ) fairly amongst the players $\mathbb{P} = \{\mathcal{S}, w\}$, where the NBS [40] method is a good candidate for that. Let $\boldsymbol{R}$ be a closed and convex subset that represents the set of payoff allocations that the players can achieve if SBSs share the time slot with WAPs and $\boldsymbol{d}$ is the set of disagreement payoffs. Therefore, the utilities of this game are $U_w = R_w(\tau) - R^{\min}_w = V_w(R^{\max}_{w,v} \cdot \tau - R^{\min}_{w,v})$ and $U_\mathcal{S} = \sum_{i \in \mathcal{S}} \sum_{j \in \mathcal{U}'_i} U_{i,j} = \sum_{i \in \mathcal{S}} \sum_{j \in \mathcal{U}'_i} \log(R_{i,j}(\tau, \boldsymbol{x}_i, \boldsymbol{y}_i) - R^l_{i,j}(\boldsymbol{x}_i)) = \sum_{i \in \mathcal{S}} \sum_{j \in \mathcal{U}'_i} \log((1-\tau) R^u_{i,j}(\boldsymbol{y}_i))$, respectively, in each time slice.

Now NBS can give us a unique solution concept [40] from the set of payoff $\boldsymbol{R}$ that satisfies the following:

$$\boldsymbol{r}^*(\tau) = \phi(\boldsymbol{R}, \boldsymbol{d}) \in \underset{\boldsymbol{r} \in \boldsymbol{R}}{\operatorname{argmax}} \prod_{p \in \mathbb{P}} U_p. \tag{19}$$

Hence, we need such a τ that will maximize the value of $\mathbf{r}(\tau)$ with fixed $\boldsymbol{y}_i, \forall i \in \mathcal{S}$ in (19). If we denote that optimal sharing time as τ^*, then that value is given in Theorem 3.

Theorem 3: With a given allocation $\boldsymbol{y}$, the optimal time slot allocation for WAPs by a given set of SBSs is $\tau^* = \max\{\frac{(\alpha+\beta+1) - \sqrt{(\alpha+\beta+1)^2 - 2\alpha(\beta+\delta)}}{\alpha}, \tau_0\}$, where $\alpha = \sum_{i \in \mathcal{S}} |\mathcal{U}'_i|$, $\beta = \sum_{i \in \mathcal{S}} \sum_{j \in \mathcal{U}'_i} \log R^u_{i,j}(\boldsymbol{y}_i)$ and $\delta = \frac{R^{\min}_{w,v}}{R^{\max}_{w,v}}$.

Proof: Taking the first-order derivative of (19) with respect to τ, we get as follow:

$$\frac{d\mathbf{r}(\tau)}{d\tau} = \frac{d}{d\tau}\{U_w U_S\}. \tag{20}$$

Now substituting the values of U_S and U_w into (20), we have:

$$\begin{aligned} \frac{d\mathbf{r}(\tau)}{d\tau} &= \left[\sum_{i \in \mathcal{S}} \sum_{j \in \mathcal{U}'_i} \log\{(1-\tau) R^u_{i,j}(\boldsymbol{y}_i)\} \right] V_w R^{\max}_{w,v} \\ &+ V_w(\tau \cdot R^{\max}_{w,v} - R^{\min}_{w,v}) \left[\frac{-\sum_{i \in \mathcal{S}} \sum_{j \in \mathcal{U}'_i} R^u_{i,j}(\boldsymbol{y}_i)}{\sum_{i \in \mathcal{S}} \sum_{j \in \mathcal{U}'_i} (1-\tau) R^u_{i,j}(\boldsymbol{y}_i)} \right]. \end{aligned} \tag{21}$$

Taking the derivate of (21) w.r.t. τ again, we get:

$$\frac{d^2\mathbf{r}(\tau)}{d\tau^2} = -V_w \left[\frac{R^{\max}_{w,v} - R^{\min}_{w,v}}{(1-\tau)^2} + \frac{R^{\max}_{w,v}}{(1-\tau)} \right] \tag{22}$$

As all the terms on the right side of (22) are positive, $R^{\max}_{w,v} > R^{\min}_{w,v}$, and $\tau \in [0,1]$, so $\frac{d^2\mathbf{r}(\tau)}{d\tau^2} < 0$. Therefore, $\mathbf{r}(\tau)$ is quasi-concave with respect to τ. Accordingly, when the first derivative of $\mathbf{r}(\tau)$ w.r.t. τ is equal to zero, the utility value achieves its maximum. Hence, we get from (21):

$$\begin{aligned} (1-\tau) R^{\max}_{w,v} & \left[\sum_{i \in \mathcal{S}} \sum_{j \in \mathcal{U}'_i} \log(1-\tau) + \sum_{i \in \mathcal{S}} \sum_{j \in \mathcal{U}'_i} \log R^u_{i,j}(\boldsymbol{y}_i) \right] \\ & - \tau \cdot R^{\max}_{w,v} + R^{\min}_{w,v} = 0. \end{aligned} \tag{23}$$

By using the Taylor's series in case of $\tau < 1$, we get as follows:

$$\log(1-\tau) = -\tau - \frac{\tau^2}{2} - o(\tau) \tag{24}$$

Now replace the value of $\log(1-\tau)$ in (23) and rearrange it by keeping the second-order approximation in τ, we get:

$$\begin{aligned} \frac{\sum_{i \in \mathcal{S}} |\mathcal{U}'_i|}{2} \tau^2 &- \left(\sum_{i \in \mathcal{S}} |\mathcal{U}'_i| + \sum_{i \in \mathcal{S}} \sum_{j \in \mathcal{U}'_i} \log R^u_{i,j}(\boldsymbol{y}_i) + 1 \right) \tau \\ &+ \sum_{i \in \mathcal{S}} \sum_{j \in \mathcal{U}'_i} \log R^u_{i,j}(\boldsymbol{y}_i) + \frac{R^{\min}_{w,v}}{R^{\max}_{w,v}} = 0. \end{aligned} \tag{25}$$

By solving (25), we get as follows:

$$\tau = \frac{(\alpha+\beta+1) \pm \sqrt{(\alpha+\beta+1)^2 - 2\alpha(\beta+\delta)}}{\alpha}, \tag{26}$$

where $\alpha = \sum_{i \in \mathcal{S}} |\mathcal{U}'_i|$, $\beta = \sum_{i \in \mathcal{S}} \sum_{j \in \mathcal{U}'_i} \log R^u_{i,j}(\boldsymbol{y}_i)$ and $\delta = \frac{R^{\min}_{w,v}}{R^{\max}_{w,v}}$. If we take the $'+'$ symbol between the two terms of the numerator, then $\tau > 1$ which is impossible. Thus, we get from (26) the following:

$$\tau = \frac{(\alpha+\beta+1) - \sqrt{(\alpha+\beta+1)^2 - 2\alpha(\beta+\delta)}}{\alpha}, \tag{27}$$

which implies,

$$\tau^* = \max\left\{ \frac{(\alpha+\beta+1) - \sqrt{(\alpha+\beta+1)^2 - 2\alpha(\beta+\delta)}}{\alpha}, \tau_0 \right\}. \tag{28}$$

The right side of (28) depends on the allocation of unlicensed resource $\boldsymbol{y}_i, \forall i \in \mathcal{S}$, the number of active users associated with WAP $w \in \mathcal{W}$ and the number of SBSs S in the considered area. ■

Algorithm 3: Alternative Maximization for LTE-U Throughput.

1: **Input**: $\mathcal{S}, \delta, \tau_0$
2: **Output**: $\boldsymbol{y}_i, \forall i \in \mathcal{S}$ and τ
3: Initialize: $t = 0$, $\tau^t = 0.5$
4: **repeat**
5: Each $i \in \mathcal{S}$ determines $\boldsymbol{y}_i^t$ by using Alg. 2 with τ^t
6: Each $i \in \mathcal{S}$ determines $\beta_i^t = \sum_{j \in \mathcal{U}_i^{'}} \log R_{i,j}^u(\boldsymbol{y}_i)$ and sends β_i^t, and $|\mathcal{U}_i^{'}|$ to the arbitrator
7: Arbitrator determines $\alpha = \sum_{i \in \mathcal{S}} |\mathcal{U}_i^{'}|$, $\beta = \sum_{i \in \mathcal{S}} \beta_i^t$
8: $t \leftarrow t + 1$
9: Arbitrator determines τ^t with the help of (28) considering α, β, δ and τ_0
10: Arbitrator informs τ^t to $\forall i \in \mathcal{S}$
11: **until** convergence

C. Alternative Throughput Maximization for LTE-U Coexistence

For a fixed set of SBSs and WAPs (with their associated users), we can find $\boldsymbol{y}_i^*$ and τ^* by using the alternative maximization approach shown in Algorithm 3. With a given τ, each SBS can allocate ($\boldsymbol{y}_i$) its resources to get a maximum U_i by using Algorithm 2 (line 5). Now with the given $\boldsymbol{y}_i$ and other information, the arbitrator can find τ^t (line 9). The process (lines 5–10) continues until it converges. Algorithm 3 will converge after a finite number of steps, and it tries to maximize the objective with limited resources in each step. This algorithm will converge to some local optimum.

Theorem 4: Algorithm 3 produces a stable and local optimal solution.

Proof: For a given τ and $\mathcal{C}_u^i$, each SBS $i \in \mathcal{S}$ produces a stable matching (following Theorems 1 and 2, shows in line 5 of Algorithm 3) at each iteration and thus, the LTE-U system is stable. Moreover, from Theorem 1, Algorithm 2 gives us a Pareto optimal matching $\Omega_{i,t}^*$ and hence, $\Omega_{i,t}^* \succ \Omega_{i,t}^{'}$, where $\Omega_{i,t}^{'}$ is any other feasible matching between $\mathcal{U}_i^{'}$ and $\mathcal{C}_u^i$ at tth iteration. Thus, $U_i(\Omega_{i,t}^*) > U_i(\Omega_{i,t}^{'})$ for every SBS $i \in \mathcal{S}$ and a non-decreasing function of binary variable $\boldsymbol{y}_i^t$. So, every SBS produces a stable and local optimal solution for each iteration. Furthermore, the arbitrator finds a new optimal τ^* (shown in line 9 of Algorithm 3) depending on the updated information from the SBSs, and this process continues until it converges. Therefore, the outcome of the Algorithm 3 is stable and local optimal solution for the original problem. ■

V. Performance Evaluation Criteria and Simulation Results

We verify the performance of the system based on efficiency and fairness. The efficiency of each SBS $i \in \mathcal{S}$ is the ratio of the total achievable throughput of all of its users to the total number of users. The system efficiency is the mean of efficiencies over all the SBSs. To measure the fairness in each SBS $i \in \mathcal{S}$, we use the proportion of unsatisfied users ($\mathcal{U}_i^u$), and also Jain's fairness index [41]. Both of these cases are outlined as follows:

$$\phi_i = 1 - \frac{|\mathcal{U}_i^u|}{|\mathcal{U}_i|}.$$

$$\psi_i = \frac{\left(\sum_{j \in \mathcal{U}_i} \frac{R_{i,j}}{Q_{i,j}}\right)^2}{|\mathcal{U}_i| \cdot \sum_{j \in \mathcal{U}_i} \left(\frac{R_{i,j}}{Q_{i,j}}\right)^2}. \tag{29}$$

For system level fairness, we use the mean of both ϕ_i and ψ_i over the SBSs and are represented as follows:

$$\phi = \frac{\sum_{i \in \mathcal{S}} \phi_i}{S}, \psi = \frac{\sum_{i \in \mathcal{S}} \psi_i}{S}. \tag{30}$$

TABLE III
Value of the Principal Simulation Parameters

Symbol	Value	Symbol	Value
S	5	$\lvert\mathcal{U}_i\rvert, \forall i$	50
B_l	180 kHz	$\lvert\mathcal{C}_i^u\rvert, \forall i$	50
B_u	180 kHz	$\lvert\mathcal{C}_u\rvert$	$c * 100, \forall c$
$P_i^l, \forall i$	19 dBm	$P_i^u, \forall i$	17dBm
σ^2	-114 dBm	G	-33.5dB
α	3	$\mathcal{C}$	{1,2,5}
$V_w, \forall w$	5	W	5

TABLE IV
QoS Requirements of Multimedia Applications

Application	Min Requirement (kbps)
HD video streaming	800
Video conferencing	700
VoIP	512
Audio streaming	320

SBSs and their corresponding users are distributed randomly in the considered area of radius 150 m. The Wi-Fi network operates based on the IEEE 802.11n protocol over the 5 GHz band using the request to send/clear to send (RTS/CTS) mechanism. SBSs also work in the same unlicensed band as WAPs. The main simulation parameters for the SBSs are shown in Table III and the Wi-Fi parameters are chosen similarly to [36]. We assume that SBSs use SDL with the help of CA when the QoS of the applications is not satisfied with the licensed spectrum. For our simulation, we use typical QoS requirements for multimedia applications as indicated in [42] and shown in Table IV. We have compared the performance of the proposed LTE-U method with LTE-A, LTE-U with no cooperation among SBSs indicated as LTE-U (NC) and LTE-U with randomly chosen users namely LTE-U (Random). Fig. 3 clearly shows that Algorithm 3 converges after a finite number of iterations. To compare the performance, we take 1000 runs for all methods. Fig. 4 also shows that the objective value for Algorithm 3, with a small network of single SBS, and it is very close to the optimal objective value. The performance gap between these two values is about 4.18% for 10 users, shown in Fig. 4.

In Fig. 5, we present the empirical cumulative distribution function (ECDF) of the achieved rate per user for different numbers of unlicensed channels. Fig. 5 shows that the achieved rate per user resulting from the proposed method is higher than the other methods for all the considered cases. Fig. 5(a) shows that LTE-A and LTE-U (NC) yield less than 420 kbps in 60% of the cases, while LTE-U (Random), and LTE-U (Proposed) can

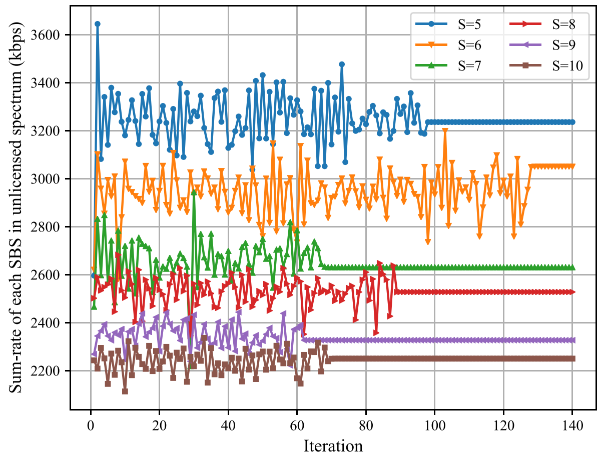

Fig. 3. Convergence of algorithm 3 for a different number of SBSs in the same unlicensed band.

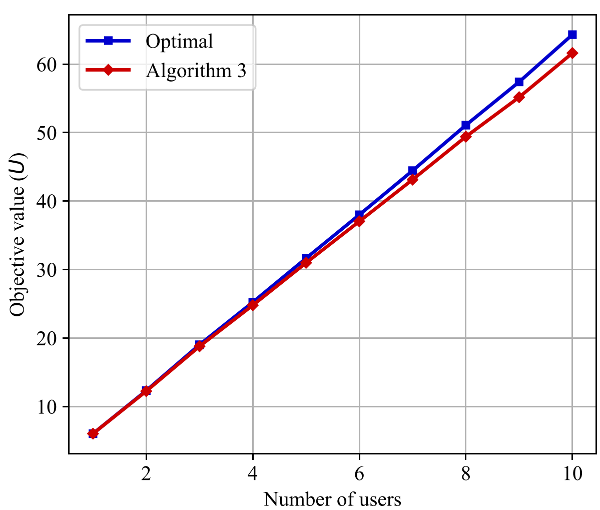

Fig. 4. Comparison of objective value of original optimization problem (13).

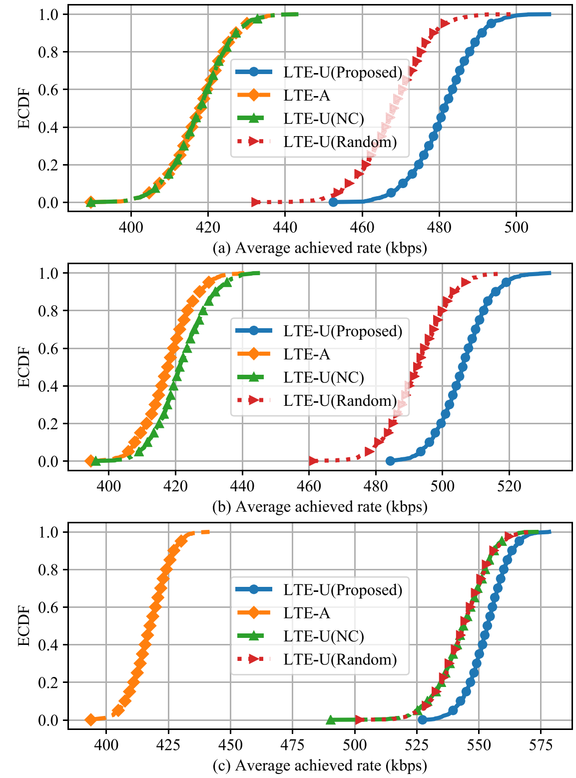

Fig. 5. Comparison of per user achieved rate for 5 SBSs. (a) Single unlicensed channel. (b) Two unlicensed channels. (c) Five unlicensed channels.

provide more than 480 kbps in 10% and 60% of cases, respectively. On average, the rate of the proposed method is 2.71%, 13.20% and 13.20% better than that of LTE-U (Random), LTE-U (NC) and LTE-A, respectively. Fig. 5(b) shows that LTE-U (NC) results in a rate that is lower than than 420 kbps in 40% of cases, while LTE-U (Random), and LTE-U (Proposed) can provide more than 500 kbps in 20%, and 80% of cases, respectively. On average, the rate of the proposed method is 2.67%, 16.68% and 17.48% better than that of LTE-U(Random), LTE-U(NC) and LTE-A respectively. Fig. 5(c) shows that LTE-U (NC) and LTE-U (Random) result in a rate that is higher than 550 kbps in 30% of cases, while LTE-U(Proposed) can yield more than 550 kbps in more than 60% of cases. On average, the rate of the proposed method is 1.75%, 1.75%, and 24.53% better than that of LTE-U (Random), LTE-U (NC) and LTE-A respectively. Fig. 5 also indicates that the achieved rate increases for LTE-U (NC), LTE-U (Random) and LTE-U (Proposed) with an increasing number of unlicensed channels as each SBS obtains more unlicensed resources for that. Meanwhile it affects nothing to LTE-A as it only use the same licensed resources. We also demonstrate that the differences of the achieved rates between the proposed method and LTE-U (Random) decrease with an increasing number of channels because their serving user sets are more common with more unlicensed resources. The achieved rate increases for LTE-U (NC) with the increasing number of unlicensed channels as the number of interferer SBSs decreases. In Fig. 6, we compare of per user achievable rate among the different methods for varying numbers of SBSs and channels. Fig. 6 reveals that the proposed method gives a better achieved rate per user than the other methods in all possible cases. From this figure, we can also see that, for an increasing number of SBSs, these rates are the same for LTE-A since it does not use unlicensed channels. However, for all other methods the rates will decrease as the amount of unlicensed resources decreases with an increasing number of SBSs. With a fixed number of SBSs, the rates increase with an increasing number of channels as the SBSs obtain more unlicensed resources to use. More specifically, the proposed method achieves 9.64%, 9.54%, and 2.33% better rate than LTE-A, LTE-U (NC), and LTE-U (Random) respectively for single unlicensed channel in case of 10 SBSs. The proposed method also achieves 13.15%, 13.15%, and 2.62% more rate for two unlicensed channels and 19.02%, 19.00%, and 2.54% more for five unlicensed channels than LTE-A, LTE-U (NC), and LTE-U (Random) respectively for 10 SBSs.

In Fig. 7, we present a comparison of unsatisfied users for different methods. Fig. 7 shows that the number of unsatisfied users resulting from the proposed method is lower than that of all other methods for all cases. Fig. 7(a) shows that the median of unsatisfied users is 60%, 60%, 45%, and 39% for LTE-A, LTE-U (NC), LTE-U (Random), and LTE-U (Proposed) respectively. In Fig. 7(b), the median of unsatisfied user rates are 60%,

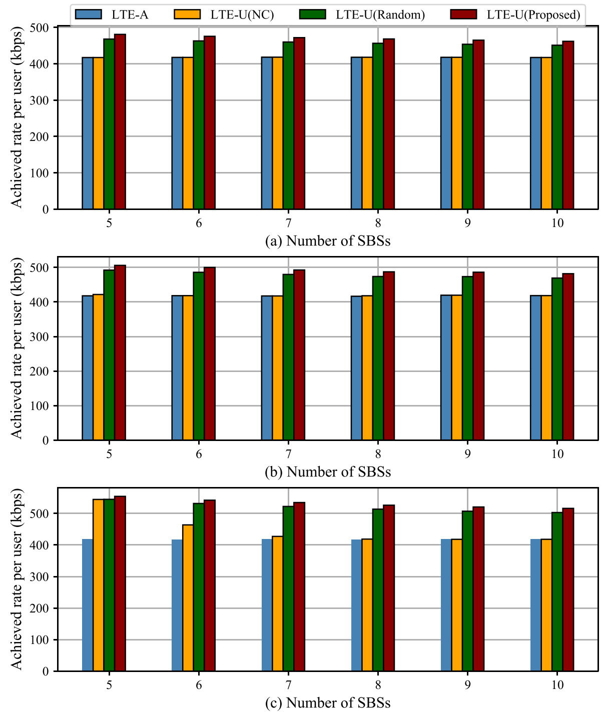

Fig. 6. Comparison of the achieved rate per user with varying number of SBSs. (a) Single unlicensed channel. (b) Two unlicensed channels. (c) Five unlicensed channels.

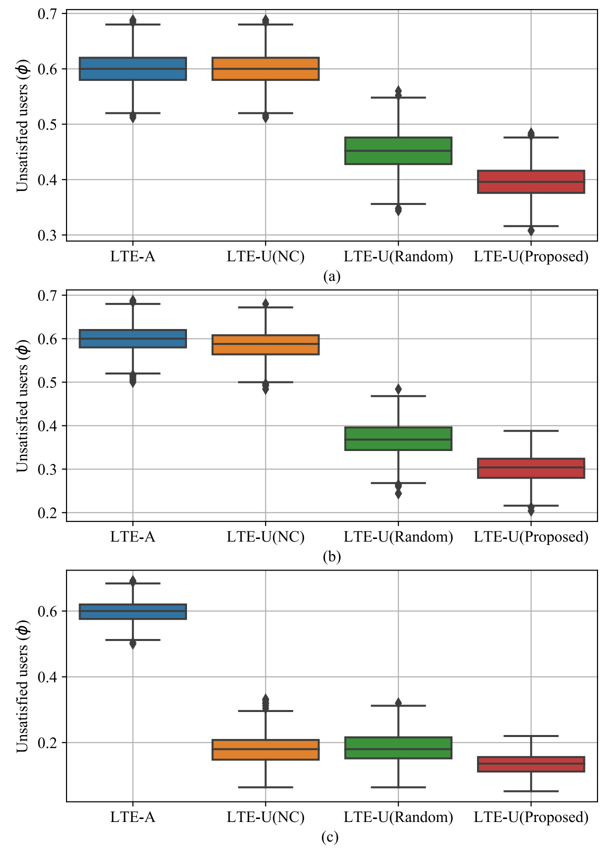

Fig. 7. Comparison of unsatisfied users for 5 SBSs. (a) Single unlicensed channel. (b) Two unlicensed channels. (c) Five unlicensed channels.

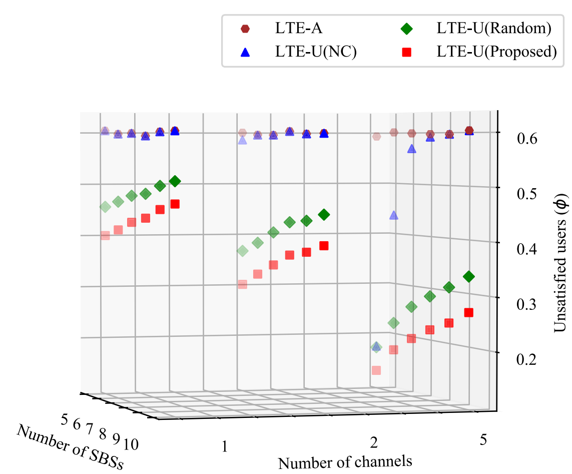

Fig. 8. Comparison of the unsatisfied users with varying number of SBSs and channels.

58%, 37%, and 30% for LTE-A, LTE-U (NC), LTE-U (Random), and LTE-U (Proposed) respectively. Meanwhile these values are 60%, 18%, 18%, and 12% for the same respective methods as shown in Fig. 7(c). The percentage of unsatisfied users remains the same in all the three cases for LTE-A, as it uses only the fixed licensed spectrum. However, the percentages decrease with an increasing number of unlicensed channels for the other three methods due to the availability of additional unlicensed resources for each SBS. Moreover, the differences among the proposed method, LTE-U (NC), and LTE-U (Random) decrease with increasing number of unlicensed channels as the number of interferer SBSs decreases in LTE-U (NC) while the probability of serving more users who are common in LTE-U (Random) and LTE-U (Proposed) increases. In Fig. 8, we compare of unsatisfied users among the different methods for varying numbers of SBSs and channels. Fig. 8 also shows that the number of unsatisfied users increases with an increasing number of SBSs for LTE-U (NC), LTE-U (Random), and LTE-U (Proposed) as the unlicensed resource decreases. For a fixed number of SBSs, the unsatisfied users decreases with an increasing number of channels, as each SBS gets more resources during the process. Particularly, the proposed method reduces unsatisfied users 13.00%, 13.00%, and 4.05% than LTE-A, LTE-U (NC), and LTE-U (Random) respectively for 10 SBSs and single unlicensed channel. The proposed method also decreases unsatisfied users 20.25%, 20.25%, and 5.61% for two channels and 33.26%, 33.21%, and 6.59% for five channels than LTE-A, LTE-U(NC), and LTE-U(Random) respectively for 10 SBSs.

In Fig. 9, we present the ECDF of fairness scores resulting from the various approaches considered as the number of unlicensed channels varies. Fig. 9 shows that the fairness scores resulting from the proposed method is higher than all of the other baselines, for all the considered cases. Fig. 9(a) shows that LTE-A and LTE-U (NC) can achieve a fairness score of less than 0.775 are almost sure, whereas LTE-U (Random), and LTE-U (Proposed) can achieve at least the same fairness score in 32.7% and 85.4% of cases, respectively. On average, the fairness score of the proposed method is 8.60%, 8.60%, and 3.10% better than that of LTE-A, LTE-U (NC) and LTE-U (Random), respectively. Fig. 9(b) shows that LTE-A and LTE-U (NC) must provide a fairness score lower than than 0.775, while LTE-U

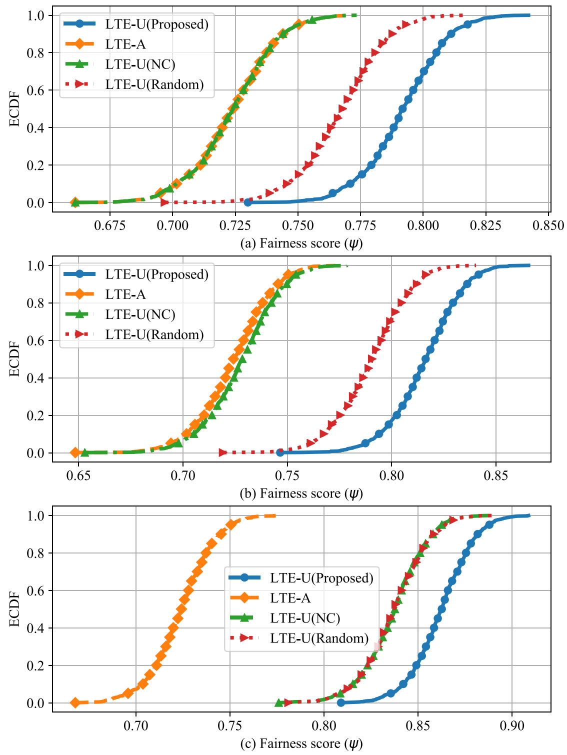

Fig. 9. Comparison of fairness 5 SBSs. (a) Single unlicensed channel. (b) Two unlicensed channels. (c) Five unlicensed channels.

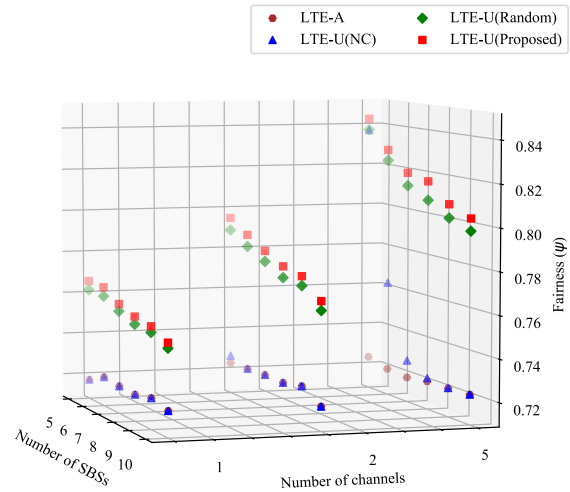

Fig. 10. Comparison of fairness with varying number of SBSs and channels.

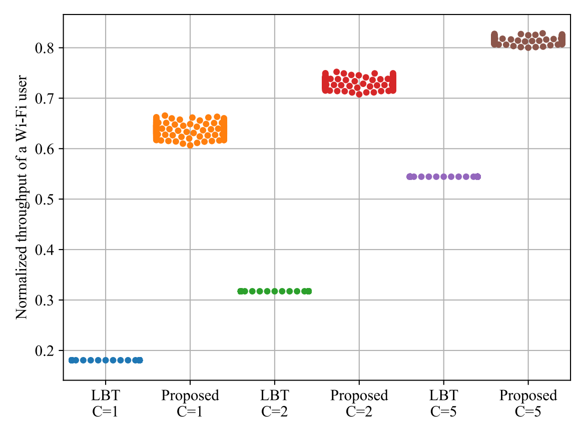

Fig. 11. Comparison of Wi-Fi user's normalized throughput with 5 SBSs and varying number of unlicensed channels (C).

(Random), and LTE-U (Proposed) can achieve fairness scores of more than 0.80 in 28.4%, and 82.90% of the cases, respectively. The mean of the fairness score of the proposed method is 11.25%, 10.78%, and 3.14% better than that of LTE-A, LTE-U (NC) and LTE-U (Random), respectively. Fig. 9(c) shows that LTE-U (NC), LTE-U (Random), and LTE-U (Proposed) achieve fairness scores of at least 0.85 in 21.40%, 23.10%, and 78.50% of cases, respectively. On average, the fairness score of the proposed method is 16.04%, 2.93%, and 2.91% better than that of LTE-A, LTE-U (NC) and LTE-U (Random), respectively. Fig. 9 also indicates that the fairness score increases for LTE-U (NC), LTE-U (Random), and LTE-U (Proposed) with an increasing number of unlicensed channels as each SBS obtains more unlicensed resources to be used for it's unsatisfied users. Meanwhile it affects nothing to LTE-A as it only depends on the same licensed resources. Moreover, the proposed method has less difference with LTE-U (Random) in fairness scores, shown in Figs. 9(a), 9(b), and 9(c), because we choose the same number of unsatisfied users for LTE-U (Random) as of the proposed method. In Fig. 10, we compare of fairness among the users for the different methods for varying numbers of SBSs and channels. Fig. 10 shows that the fairness score of the proposed method is higher than that of the other three methods for all cases. The figure also shows that these scores are the same for LTE-A in all the cases, but they decrease with an increasing number of SBSs for different numbers of channels for LTE-U (NC), LTE-U (Random), and LTE-U (Proposed) due to the reduced amount of unlicensed resources. However, these fairness scores increase with an increasing number of channels for a fixed number of SBSs. Precisely, the fairness scores of the proposed method are 3.07%, 3.07%, and 0.25% higher than LTE-A, LTE-U (NC), and LTE-U (Random) respectively for 10 SBSs and single unlicensed channel. Moreover, the proposed method is 4.80%, 4.80%, and 0.43% more fair for two channels and 8.11%, 8.10%, and 0.58% more fair for five channels than LTE-A, LTE-U (NC), and LTE-U (Random) respectively for the same number of SBSs. Thus, the difference of fairness scores of the proposed method with other methods increases with an increasing amount of unlicensed resources as the proposed method utilize the resources better way to meet the QoS of their users.

In Fig. 11, we show a comparison of the normalized throughput of Wi-Fi users between the proposed method and the LBT method considering 5 SBSs in the conflicting region. Fig. 11 shows that the proposed method protects Wi-Fi users far better than the basic LBT mechanism in all the cases. Both the proposed method and LBT provide a higher rate to the Wi-Fi users for an increasing number of channels as less APs need to share the same channel. However, the proposed method achieves 71.70%, 56.53%, and 33.30% higher average rate than LBT mechanism for single, two, five channels cases respectively. In Fig. 12, we show a comparison of the normalized throughput of Wi-Fi users between the proposed method and LBT with

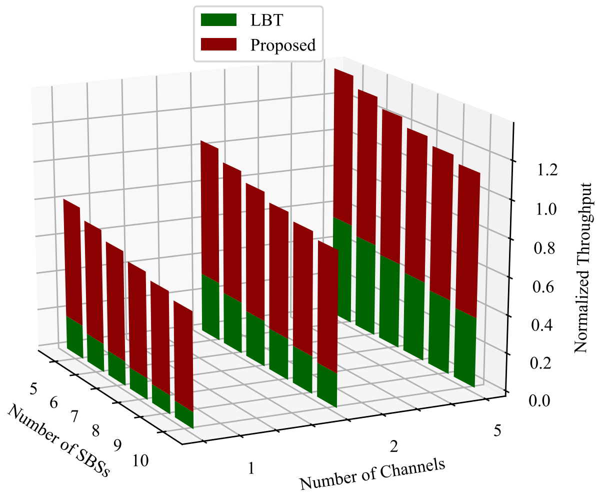

Fig. 12. Comparison of Wi-Fi user's normalized throughput.

a varying number of SBSs and channels. This shows that the proposed method shields Wi-Fi users better than LBT for all possible combinations. With an increasing number of SBSs, the outputs are reduced for both the proposed method and LBT, as this increases the competition among APs in a fixed channel. For a fixed number of SBSs, both methods produce a better throughput for a growing number of channels, as this reduces the competition among the APs. The proposed method can guarantee 82.98%, 71.68%, and 50.96% higher rates than LBT for 10 SBSs in cases of single, two, and five channels respectively. Moreover, the proposed method for 10 SBSs achieves 31.54%, and 15.41% higher wi-fi rate for five channels than its' single and two channels respectively. However, these figures are 76.25%, and 51.15% for the case of LBT. Thus, the proposed method provides more stable throughput than LBT for resource constraint situation.

VI. Conclusion

In this paper, we have proposed a novel approach to coexist LTE-U and Wi-Fi networks in the same unlicensed spectrum. We have formulated it as a sum-rate maximization problem of LTE-U system and solved with the help of game-theoretic approach. We have solved the time sharing problem between SBSs and WAPs by using NBG, whereas the resource allocation problem of SBS is solved with the help of one-sided matching game. Simulation results show that the proposed approach provides better average achieved rates for the users, as well as less unsatisfied users, and better fairness than LTE-A, LTE-U (NC) and LTE-U (Random) methods. Moreover, the proposed approach protects Wi-Fi users in a far better way than does basic LBT. In the future, we will try to improve the performance metrics using a more carefully designed mechanism.

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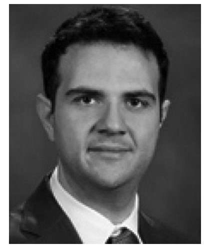
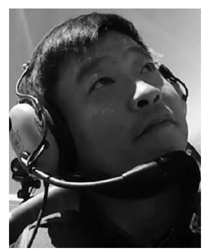
Anupam Kumar Bairagi (S’17–M’18) received the B.Sc. and M.Sc. degrees in computer science and engineering from Khulna University, Khulna, Bangladesh. He is currently working toward the Ph.D. degree from Kyung Hee University, Seoul, South Korea, for which he was awarded a scholarship in 2014. He is a Faculty Member in the discipline of Computer Science and Engineering, Khulna University. His research interests includes wireless resource management in 5G, cooperative communication, and game theory.

Nguyen H. Tran (S’10–M’11–SM’18) received the B.S. degree from the Ho Chi Minh City University of Technology, Ho Chi Minh City, Vietnam, and the Ph.D. degree from Kyung Hee University, Seoul, South Korea, in electrical and computer engineering, in 2005 and 2011, respectively. Since 2012, he has been an Assistant Professor with the Department of Computer Science and Engineering, Kyung Hee University. His research interest is to applying analytic techniques of optimization, game theory, and stochastic modeling to cutting-edge applications such as cloud and mobile edge computing, data centers, heterogeneous wireless networks, and big data for networks. He was the recipient of the Best KHU Thesis Award in engineering in 2011 and Best Paper award at the IEEE ICC 2016. He is the Editor of the IEEE TRANSACTIONS ON GREEN COMMUNICATIONS AND NETWORKING.



Walid Saad (S’07–M’10–SM’15) received the Ph.D. degree from the University of Oslo, Oslo, Norway, in 2010. He is currently an Assistant Professor and the Steven O. Lane Junior Faculty Fellow with the Department of Electrical and Computer Engineering, Virginia Tech, Blacksburg, VA, USA, where he leads the Network Science, Wireless, and Security Laboratory, within the Wireless@VT Research Group. His research interests include wireless networks, game theory, cybersecurity, and cyber-physical systems. He is the recipient of the National Science Foundation CAREER award in 2013, the AFOSR summer faculty fellowship in 2014, and the Young Investigator Award from the Office of Naval Research in 2015. He has authored/coauthored of five conference Best Paper Awards at WiOpt in 2009, ICIMP in 2010, IEEE WCNC in 2012, IEEE PIMRC in 2015, and IEEE SmartGridComm in 2015. He is the recipient of the 2015 Fred W. Ellersick Prize from the IEEE Communications Society. He serves as an editor for the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, the IEEE TRANSACTIONS ON COMMUNICATIONS, and the IEEE TRANSACTIONS ON INFORMATION FORENSICS AND SECURITY.



Zhu Han (S’01–M’04–SM’09–F’14) received the B.S. degree in electronic engineering from Tsinghua University, Beijing, China, in 1997, and the M.S. and Ph.D. degrees in electrical and computer engineering from the University of Maryland, College Park, MD, USA, in 1999 and 2003, respectively. From 2000 to 2002, he was an R&D Engineer with JDSU, Germantown, MD, USA. From 2003 to 2006, he was a Research Associate with the University of Maryland. From 2006 to 2008, he was an Assistant Professor with Boise State University, Boise, ID, USA. He is a Professor with the Electrical and Computer Engineering Department as well as with the Computer Science Department, University of Houston, Houston, TX, USA. His research interests include wireless resource allocation and management, wireless communications and networking, game theory, big data analysis, security, and smart grids. He was the recipient of the National Science Foundation Career Award in 2010, the Fred W. Ellersick Prize of the IEEE Communication Society in 2011, the EURASIP Best Paper Award for the *Journal on Advances in Signal Processing* in 2015, IEEE Leonard G. Abraham Prize in the field of Communications Systems (best paper award in IEEE JSAC) in 2016, and several Best Paper Awards in IEEE conferences. He is currently the IEEE Communications Society Distinguished Lecturer.

Choong Seon Hong (S’95–M’97–SM’11) received the B.S. and M.S. degrees in electronic engineering from Kyung Hee University, Seoul, South Korea, in 1983 and 1985, respectively, and the Ph.D. degree from Keio University, Minato, Japan, in 1997. In 1988, he joined Korea Telecom, where he worked on broadband networks as a member of Technical Staff. In September 1993, he joined Keio University. He worked with the Telecommunications Network Laboratory, Korea Telecom, as a Senior Member of Technical Staff and the Director of the Networking Research Team until August 1999. Since September 1999, he has been a Professor with the Department of Computer Science and Engineering, Kyung Hee University. His research interests include future Internet, ad hoc networks, network management, and network security. In addition, he is currently an Associate Editor for the IEEE TRANSACTIONS ON NETWORK AND SERVICE MANAGEMENT, *International Journal of Network Management*, and *Journal of Communications and Networks* and an Associate Technical Editor of the IEEE COMMUNICATIONS MAGAZINE. He is a member of ACM, IEICE, IPSJ, KIISE, KICS, KIPS, and OSIA. He has served as the General Chair, a TPC Chair/Member, or an Organizing Committee Member for international conferences such as NOMS, IM, APNOMS, E2EMON, CCNC, ADSN, ICPP, DIM, WISA, BcN, TINA, SAINT, and ICOIN.