IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received August 13, 2018, accepted September 1, 2018, date of publication September 6, 2018,
date of current version September 28, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2868875

QoE-Enabled Unlicensed Spectrum Sharing in 5G: A Game-Theoretic Approach

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This work was supported by the Ministry of Science and ICT, South Korea, through the Grand Information Technology Research Center Support Program under Grant IITP-2018-2015-0-00742 supervised by the Institute for Information and Communications Technology Promotion).

ABSTRACT Spectrum sharing is an important aspect of 5G new radio, as it plays a complementary role for fulfilling diversified service requirements. This paper studies unlicensed spectrum sharing, namely, local thermal equilibrium (LTE) over unlicensed bands (LTE-U), for providing a better quality of experience (QoE) in 5G networks. Specifically, unlicensed band selection and resource allocation (time, licensed, and unlicensed) are jointly designed, and an optimization problem is formulated with the objective of maximizing LTE users' QoE [measured in mean opinion score (MOS)] while protecting incumbent wireless systems such as Wi-Fi in the unlicensed spectrum. To solve the multi-player interaction in this spectrum space fairly, we employ a game-theoretic approach. A virtual coalition formation game (VCFG) is used to solve the unlicensed band selection problem. The outcome of the VCFG defines the optimization problem within each coalition. This optimization problem is then decomposed into two sub-problems: 1) time-sharing problem between the LTE-U and Wi-Fi systems and 2) a resource allocation problem for the LTE-U system. The cooperative Kalai–Smorodinsky bargaining solution is used for solving the first sub-problem, whereas the Q-learning algorithm is used for solving the second. VCFG and Q-learning-based resource allocation algorithms are proposed in this paper. In addition, the stability of VCFG and optimal sharing time are also proved in this paper. Simulation results show the advantages of the proposed approach over other baseline methods in terms of the MOS, percentage of unsatisfied users, and fairness. The results also show 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, spectrum sharing, coexistence, QoE, VCFG, KSBS, Q-learning.

I. INTRODUCTION

Recent Cisco studies [1] have pointed that the number of mobile connected devices and the amount of mobile wireless traffic will continually rise in the foreseeable future, with mobile video data composing a large portion of this traffic. Considering such traffic challenges, a wide range of applications, including augmented reality, e-health, e-banking, and e-education, have emerged with diverse service requirements [2]. The mobile application market is expected to grow with a cumulative average growth rate (CAGR) of 29.1% during the estimated period of 2015-2020 [3]. Moreover, 5G networks are going to deliver multi-gigabit, ultra-reliable, and ultra-low latency connectivity to users. Thus, the next generation fo wireless networks need significant improvement in terms of the network capacity in order to support such a large amount of mobile traffic, while also fulfilling the service provisions for different applications. Hence, availability of the spectrum is as valuable as ever with other technologies.

The licensed spectrum is not only considered to be the cornerstone of ubiquitous wireless connectivity, but is also the industry's top priority. However, the shared/unlicensed spectrum is a part of the broader vision of the 5G communication. That is why many researchers are recommending the use of free unlicensed spectra or under-utilized spectra from other legacy systems with LTE networks in order to satisfy the increasing user demands. 3GPP has already announced licensed-assisted access (LAA) of unlicensed spectrum (5 GHz and 60 GHz) in LTE for the downlink in part of its Release 13 [4] with the help of carrier aggregation (CA) technology. Moreover, cellular capacity can be increased by opportunistic use of under-utilized spectrum from other systems such as TV white space through the use of cognitive radio technologies [5]. 3GPP has also considered shared/unlicensed spectra as a new study item in 5G new radio (NR) [6]. Though the utilization of a free unlicensed spectrum can improve the capacity of cellular networks significantly without requiring substantial new investment, this will create a considerable issue for already deployed technologies such as Wi-Fi, ZigBee, and Bluetooth in the unlicensed spectrum. Thus, LTE over unlicensed bands (*LTE-U*) will introduce two major issues: (i) resource sharing (*coexistence*) with other technologies and (ii) resource allocation along with the licensed spectrum.

Coexistence mechanisms of LTE-U deployment can be categorized into three domains, namely frequency, time, and power. The goal of these mechanisms is to use separate frequencies and times between the LTE-U and Wi-Fi systems in the frequency and time domains, respectively, while the LTE-U system adjusts the transmission power to coexist in the power domain. Dynamic channel selection (DCS) [7] and dynamic channel switching [8] are examples of coexistence mechanisms in the frequency domain. There are numerous studies [9]–[21] in the time domain, but few works [22]–[25] in the power domain regarding harmonious coexistence between LTE-U and Wi-Fi systems. While the frequency domain coexistence approaches are contingent on the availability of idle channels, the power domain approaches cannot guarantee fair coexistence among two contending systems. Thus, most of the researchers in this field focus on the time domain for effective coexistence mechanisms. However, most of these works do not present closed-form solutions of the sharing time between two systems, and many of them consider only one macro base station (MBS) or one small cell base station (SBS) in their model, and hence, ignore inter-operator interference. On the other hand, most of the works consider the quality-of-service (QoS) requirements of the users for allocating unlicensed resources. However, QoS represents the network operators perspective, not the users perceived *quality of experience* (QoE). A system which is QoS fair can be QoE unfair [29]. As per our knowledge, [30] is the only study to consider QoE requirements of the users, exploiting the licensed and unlicensed spectra in 5G networks for efficient service provisioning; however, it does not consider the coexistence issue with other technologies such as Wi-Fi. Moreover, Zhang *et al.* [30] consider only a single user satisfaction mechanism that is application-specific. Hence, there is a lack of studies in the field of unlicensed resource sharing (LTE-U) that effectively considers users' perspective (QoE), coexistence issue with other incumbent technologies (i.e. WiFi) as well as inter-operators' effect to the system. Moreover, in the existing literature, the solution for representing the unlicensed band selection problem among SBSs and WAPs is rare. Furthermore, the closed-form coexistence solution for sharing time is also scarce in the time domain. Thus, the motivation of this paper is to address the aforementioned issues effectively through a game theoretic approach. In this paper, we propose a QoE-enabled unlicensed resource sharing mechanism for 5G that can deal with multiple cellular network operators (CNOs) while providing *fairness* to the Wi-Fi systems in the same unlicensed bands. More specifically, the main contributions of this paper are as follows:

- We formulate an optimization problem to maximize the QoE (measured in MOS) of LTE-U users considering coexistence issue with a Wi-Fi system.
- We solve the unlicensed band selection problem by using a *virtual coalition formation game* (VCFG) and prove the stability of the coalition formation algorithm.
- We decompose the problem of each virtual coalition (VC) into two sub-problems: time sharing and resource allocation. The time sharing problem is solved using the cooperative *Kalai-Smorodinsky bargaining solution* (KSBS) and the resource allocation problem for each SBS is solved by applying the Q-learning algorithm.
- We find an optimal solution for time sharing between the LTE-U and Wi-Fi systems and develop an algorithm for resource allocation using the Q-learning algorithm.
- We justify the advantages 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. A VCFG based analysis of the unlicensed band selection problem is represented in Section IV. The resource sharing and allocation problem of each VC is solved in Section V. In Section VI, we present numerical results and discussions. Finally, the paper is concluded in Section VII.

II. LITERATURE REVIEW

There is an overwhelming consensus among academia and industry to utilize free unlicensed spectra with LTE networks to handle the spectrum scarcity issues of wireless communications. Hence, there have been many proposals from industry and academia to use unlicensed spectra effectively. Using separate frequencies for different networks is the main mechanism in the frequency domain. In [7], Qualcomm proposes DCS for fair coexistence of LTE-U and Wi-Fi networks. In this process, SBSs try to avoid the channels currently being used by Wi-Fi by dynamically changing the channels. In the case of unavailability of a clear channel, LTE-U will choose the channel with the lowest interference level. A proportional fair DCS technique is proposed for LBT based LTE-U in order to coexist with the Wi-Fi network in [8]. They introduce a frozen period by modifying the binary exponential LBT to ensure correct channel switching decisions. This mechanism is effective for low traffic, but inefficient in dense deployment scenarios.

In the time domain, underlying mechanism is to split the time between the two systems and use accordingly. Guan and Melodia [9] propose a cognitive co-existence scheme to enable spectrum sharing between LTE-U and Wi-Fi networks. However, they do not acknowledge the inherent heterogeneity costs and the resulting model complexity does not provide an explicit solution. Yin *et al.* [10] propose an adaptive backoff window size depending on the rate requirements of LAA-UEs (user equipments) and the collision probability for coexisting with Wi-Fi. Here, they do not consider the interference from other operators in the same unlicensed band, and the LBT based mechanism suffers in dense scenarios. Chen *et al.* [11] propose a hyper access point (HAP) for providing a contention-free period to LTE-U users and a contention period for Wi-Fi users to promote coexistence. They use a bargaining game framework to solve the interaction between the two systems. However, this requires a centralized controller and does not consider inter-operator interference with the LTE-U system. In [12], a fair coexistence mechanism based on LBT between LTE-U and WLAN is proposed. They use a coalition formation game among the LTE-U base stations (BSs) to reduce the collision probability. However, the network performance of the LBT based mechanism is not sufficient in dense deployment scenarios. Chen *et al.* [13] formulated a resource allocation problem for an LTE-U system by decoupling the uplink-downlink and the licensed-unlicensed band by implementing an echo state network. Here, they protect the Wi-Fi system by splitting the time between the two systems. However, they did not find the optimal time and did not consider interference from other LTE-U BSs. To alleviate the interference between the LTE-LAA and Wi-Fi systems, Chung and Cho [14] propose a coalition game-based approach by offloading part of the data traffic from the LTE-LAA to a nearby Wi-Fi access point (WAP) with the help of an almost-blank-subframe (ABS). They did not consider inter-operator interference, and the Wi-Fi performance suffers for a large number of users. Bairagi *et al.* [15], [16] propose effective coexistence approaches based on a cooperative Nash bargaining game (NBG). They considered inter-operator interference in their model and found the optimal sharing time. Bairagi *et al.* [15] used a bankruptcy game (BG) to allocate unlicensed resources among the users, whereas a heuristic algorithm is used in [16]. In both cases, their approaches proved effective over other methods and can better protect Wi-Fi systems than does basic LBT.

Challita *et al.* [17] also use an LBT mechanism to achieve fairness between LTE-U and Wi-Fi systems in the case of unlicensed spectrum sharing. They introduce a deep reinforcement learning framework to allocate resources among the users in a multi-operators scenario. However, performance is still an important issue in LBT based mechanism, especially in dense deployment scenarios. Hu *et al.* [18] propose a decentralized Q-learning algorithm for solving the uplink-downlink resource allocation problem of LTE-U networks. However, the state space of the proposed Q-learning mechanism [18] depends on the actions of other SBSs, for which it is almost impossible to obtain real-time information. Moreover, there is no concrete solution for the sharing time in [18]. Su *et al.* [19] address the problem of coexistence between LTE-U and Wi-Fi networks by employing Q-learning for optimized duty cycles. However, determination of the state space is a difficult task in versatile wireless environments, and the results in [19] show that the Wi-Fi throughput will be significantly degraded compared to LBT and carrier-sensing adaptive transmission (CSAT).

Zhang *et al.* [20] propose a coexistence mechanism between LTE-U and Wi-Fi by formulating it as an access point (AP) selection problem using a centralized coalition formation game. The proposed approach in [20] 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-Wi-Fi coexistence. The work in [21] proposes a joint channel selection and frame scheduling optimization framework for LTE systems while considering fairness with WLAN. However, the proposed approach in [21] presents no solution for the sharing time between the two systems in the unlicensed spectrum.

Adjusting the output power of the LTE-U nodes is the underlying mechanism for coexistence between LTE-U and Wi-Fi networks in the power domain. A general framework for fair coexistence between LTE and Wi-Fi systems is proposed in [22] by leveraging a multi-antenna transmit beamforming technique for spatial reuse. The model of Yin *et al.* [22] allocates optimal power to balance the throughput of the two systems. However, the solution proposed in [22] requires gathering the channel state information (CSI) of all Wi-Fi users, which is very challenging practically speaking. A cooperative coexistence between LTE-U and Wi-Fi networks is studied in a fully centralized manner in [23]. The authors employ the software-defined networking (SDN) architecture to support logical control over the whole system to improve spectrum efficiency and assist coexistence among different networks. However, the overhead of such centralized controllers and the exchange of information among different nodes are huge in such cases. Zhang *et al.* [24] propose a multi-operator multi-user Stackelberg game for investigating the interplay between multiple operators and UEs in the unlicensed spectrum. To protect the WAPs, each operator sets an interference penalty price for each UE that causes interference with the WAP, and the UEs can choose their sub-bands of the unlicensed spectrum and determine the optimal transmit power. However, the information exchange overhead between the operators and UEs is high, and WAPs also need to share all their information with the CNOs. Gu *et al.* [25] model the interactions between LTE-U and Wi-Fi users as a stable marriage game. They protect unlicensed users by implementing an interference bar among LTE-U users. They introduce an inter-channel cooperation strategy to address the external effects of matching. However, they do not consider inter-operator interference or how WAPs need to share all their information with the LTE-U system in their model.

Cooperative communication also has emerged as a key enabler for 5G mobile wireless networks. The authors investigate the outage probability (OP) performance of mobile D2D and mobile cooperative networks in [26] and [27] respectively. Xu *et al.* [26] use incremental amplify and forward (IAF) relaying and transmit antenna selection (TAS). Based on this technique, a single transmit antenna from a set of L available ones, which maximizes the total received signal power at the receiver, is selected for transmission. They derive a closed-form OP expression for TAS and formulate minimization problem of power allocation. Xu *et al.* [27] use incremental decode-and-forward (IDF) relaying with TAS for analyzing Op performance. They also find closed-form solution for OP with optimal TAS, and conclude that power allocation parameter has influence over OP performance. Bairagi *et al.* [28] propose a collaborative communication mechanism for providing guaranteed QoS to the mobile users by taking opportunities of multi-connectivity of smart user equipments. They solve the problem by utilizing one-to-many matching game.

III. SYSTEM MODEL AND PROBLEM FORMULATION

We consider a 5G deployment scenario that consists of a set $\mathcal{B}$ of B dual-mode (which can operate on both in the licensed and unlicensed spectra) LTE-A SBSs and a set $\mathcal{W}$ of W non-overlapping WAPs, as shown in Figure 1. Both the SBSs and WAPs are responsible for the downlink operations of their users. Each SBS $i \in \mathcal{B}$ can serve a set of users $\mathcal{U}_i$, using a set of standard LTE licensed resource blocks (RBs) $\mathcal{L}_i$. Each SBS or WAP can operate in any of the unlicensed spectrum bands from $\mathcal{K} = \{1, 2, \ldots, K\}$. Each WAP $w \in \mathcal{W}$ has a set $\mathcal{U}_w$ of active users. Thus, a cellular user can be affected by some SBSs and one WAP, as the members of $\mathcal{W}$ are non-overlapping, whereas a Wi-Fi user will experience interference by various SBSs that are operating on the same unlicensed band. For the efficient management of unlicensed resources, each band $k \in \mathcal{K}$ is divided into J_k standard LTE sub-carriers and represented by the set $\mathcal{C}_k$. Each SBS can support a set of services (e.g., web browsing, file downloading, and video streaming) $\mathcal{S} = \{1, 2, \ldots, S\}$ for its users by using a set of modulation and coding schemes (MCSs) $\mathcal{M} = \{1, 2, \ldots, M\}$. For reliable communication between the SBS and a cellular user, each SBS allocates at least one licensed subchannel to its active users. 3GPP actively considers standalone (SA) mode [6] and uplink sharing [31] for true implementation of 5G. Time division duplexing (TDD) access scheme is one of the probable candidates for standalone 5G system [32] whereas time division multiplexing (TDM) based solution could be the baseline for LTE/NR uplink sharing [33]. However, in this work we consider SDL [7] mode, where SBSs use licensed spectrum as a primary carrier and unlicensed spectrum as a supplementary one. This approach will enhance the reliability of control information between the SBS and user equipments, and also increase the data rate of the users whenever required. On the other hand, it releases unlicensed spectrum when it is not required by the LTE-U users. SDL mode has been already adopted by Europe and Latin America for supporting 5G in L-band (1427 MHz - 1518 MHz) [32] and many authors have considered SDL mode operation for the SBSs in their proposals [15], [16], [34]–[36]. The main parameters used in this work are presented in Table 1.

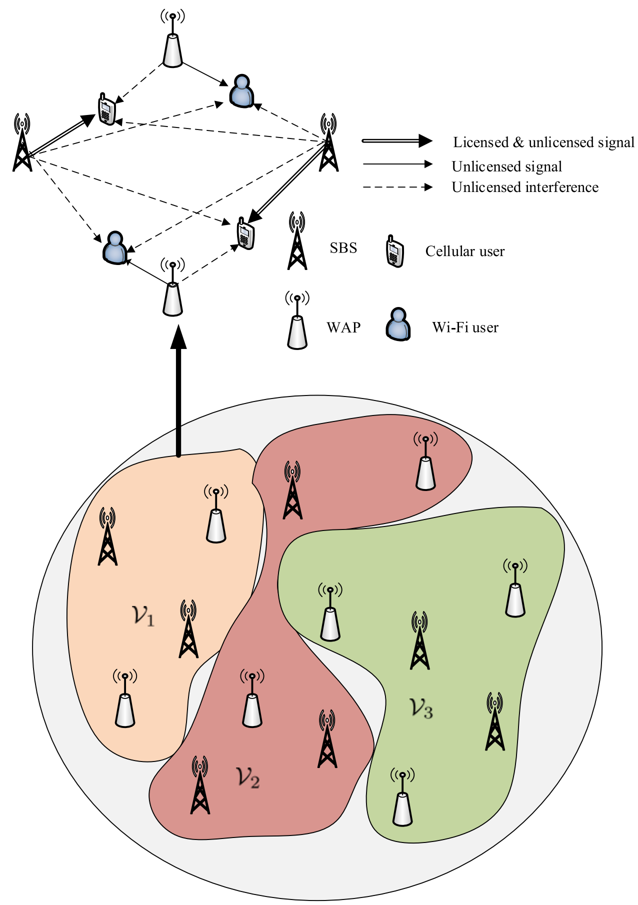

FIGURE 1. Illustration of the system model.

A. APPLICATION LAYER MODEL

QoE is application-specific, i.e., with similar network parameters, the QoE is different for different applications. This paper adopts the mean opinion score (MOS) as the QoE metric to measure user satisfaction. In the following, we describe the mapping between the transmission characteristics and MOS of different applications.

1) WEB BROWSING (WB)

Users are concerned about the page loading time in the case of web browsing. Ameigeiras *et al.* [37] present an MOS function to outfit with their experimental web browsing results,

TABLE 1. Summary of notations.

Symbol	Meaning
$\mathcal{B}$	Set of dual-mode SBSs with B elements
$\mathcal{W}$	Set of non-overlapping WAPs with W elements
$\mathcal{U}_i$	Set of users associated with SBS i
$\mathcal{L}_i$	Set of licensed RBs of SBS i
$\mathcal{K}$	Set of K traditional 20 MHz Wi-Fi bands
$\mathcal{C}_k$	Set of J_k sub-carriers of band $k \in \mathcal{K}$
$\mathcal{B}_k$	Set of SBSs who are using band $k \in \mathcal{K}$
$\mathcal{W}_k$	Set of WAPs who are using band $k \in \mathcal{K}$
$\mathcal{S}$	Set of S services
$\mathcal{M}$	Set of M modulation and coding schemes
η	Mean opinion score (MOS)
P_i^l	Transmission power of SBS i for each user in the licensed spectrum
P_i^u	Transmission power of SBS i for each user in the unlicensed spectrum
ξ	Service response time of web browsing
r	Offered rate to a user by an SBS
p_e	Packet error probability
$\boldsymbol{\alpha}_i$	Resource allocation vector for SBS i in the licensed spectrum
$\boldsymbol{\beta}_i$	Resource allocation vector for SBS i in the unlicensed spectrum
$\boldsymbol{\phi}_i$	MCS vector for SBS i
C_m	Constellation size of MCS $m \in \mathcal{M}$
n_s	Number of consecutive OFDM symbols in a RB
n_{sc}	Number of sub-carrier in a RB
t_s	OFDM symbol duration
$r_{i,j}^l$	Offered rate from SBS i to user j in the licensed spectrum
$r_{i,j}^u$	Offered rate from SBS i to user j in the unlicensed band
τ	Sharing time between the LTE-U and Wi-Fi systems
τ^0	Minimum time that the Wi-Fi system gets if each SBS acts like a WAP
γ	signal-to-interference-plus-noise ratio (SINR)
$\mathcal{A}_i$	Action space for SBS i
$\Re_i$	Reward vector of SBS i in the case of $\mathcal{A}_i$
Q_i^n	Q-value of SBS i in the case of the n^{th} action
ϑ	Learning rate parameter

shown as follows:

$$\eta^b = 5 - \frac{578}{1 + (11.77 + \frac{22.61}{\xi})^2}, \tag{1}$$

where ξ is the service response time.

2) FILE DOWNLOADING (FD)

File downloading is an elastic service. We use the following MOS-throughput [38] relationship for estimating user satisfaction in the case of file downloading applications:

$$\eta^d = a \cdot \log_{10}[b \cdot r(1 - p_e)], \tag{2}$$

where r is the current rate offered to a user, p_e is the packet error probability (PEP), and the coefficients a and b are the maximum and minimum user-perceived quality, respectively.

3) VIDEO STREAMING (VS)

The MOS value of video streaming applications is determined from the video QoE prediction model indicated in [39] shown as follows:

$$\eta^v = \frac{a_1 + a_2 \cdot f_r + a_3 \cdot \ln r}{1 + a_4 \cdot p_e + a_5 \cdot p_e^2}, \tag{3}$$

where f_r denotes the frame rate, r indicates the sender bit rate, and the coefficients $a_1, \ldots, a_5$ depend on video classes, including slight movement (SM), gentle walking (GW), and rapid movement (RM).

B. NETWORK LAYER MODEL

LTE uses the orthogonal frequency division multiple access (OFDMA) technique to allocate RB for its users. An RB consists of n_s consecutive OFDM symbols in the time domain and n_{sc} sub-carriers in the frequency domain. If SBS i allocates RB $p \in \mathcal{L}_i$ to user $j \in \mathcal{U}_i$, then $\alpha_{i,j}^p = 1$, and $\alpha_{i,j}^p = 0$ otherwise. SBSs can dynamically select an appropriate modulation and coding scheme (MCS) for each user j depending on the CSI in RB p. LTE employs the same MCS over multiple RBs for a single user in the same time. If SBS i chooses MCS $m \in \mathcal{M}$ for user $j \in \mathcal{U}_i$, then $\phi_{i,j}^m = 1$, and $\phi_{i,j}^m = 0$ otherwise, and $\sum_{m \in \mathcal{M}} \phi_{i,j}^m = 1$ for all $j \in \mathcal{U}_i$. Moreover, if r_c^m is the code rate, C_m is the constellation size, and t_s is the OFDM symbol duration associated with MCS $m \in \mathcal{M}$, then the bit rate achieved by MCS m for a single RB is given as follows:

$$r_m = \frac{r_c^m \log_2(C_m)}{t_s n_s} \cdot n_s n_{sc} = \frac{n_{sc} r_c^m \log_2(C_m)}{t_s}. \tag{4}$$

Thus, SBS i can offer the following data rate for user $j \in \mathcal{U}_i$ in the licensed spectrum:

$$r_{i,j}^l = \sum_{p \in \mathcal{L}_i} \alpha_{i,j}^p \sum_{m \in \mathcal{M}} \phi_{i,j}^m r_m. \tag{5}$$

In the unlicensed band, we consider individual sub-carriers for n_s consecutive OFDM symbol periods that can be aggregated with the licensed spectrum to improve the offered rates to the users. Thus, the SBS can achieve the following bit rate in an unlicensed sub-carrier when it uses MCS m as in (4):

$$r_m^u = \frac{r_m}{n_{sc}}. \tag{6}$$

Hence, SBS i can provide the following data rate for user $j \in \mathcal{U}_i$ in the unlicensed spectrum:

$$r_{i,j}^u = \sum_{q \in \mathcal{C}_k} \beta_{i,j}^q \sum_{m \in \mathcal{M}} \phi_{i,j}^m r_m^u, \tag{7}$$

where $\beta_{i,j}^{q} = 1$ if SBS i allocates sub-carrier $q \in \mathcal{C}_k$ to user $j \in \mathcal{U}_i$, and $\beta_{i,j}^{q} = 0$ otherwise. Therefore, the total offered rate for user $j \in \mathcal{U}_i$ is,

$$r_{i,j} = r_{i,j}^{l} + r_{i,j}^{u}. \tag{8}$$

However, the actual achieved rate for user j depends upon the PEP in both the licensed and unlicensed spectra. The PEP can be approximated from [40] as a function of the signal-to-interference-plus-noise ratio (SINR) as follows:

$$p_e = c_1 \exp\left[\frac{-c_2 \gamma^{\frac{P(\gamma)}{\bar{P}}}}{f(k(\gamma))}\right], \tag{9}$$

where

$$f(k(\gamma)) = 2^{c_3 k(\gamma)} - c_4, \tag{10}$$

and c_1, c_2, and c_3 are positive fixed constants, and c_4 is a real constant. $P(\gamma)$, $\bar{P}$, and $k(\gamma)$ represent the transmission power, average transmission power, and bit rate per symbol ($k(\gamma) = \log_2 C$), respectively.

C. DELIVERABLE RATE OF WAP

When WAP only uses an unlicensed band, it can utilize the maximum capacity $R_w^{\max}$ for its users. When some SBSs $\mathcal{B}_k$ use the same unlicensed band k as the WAP, the performance of WAP will be affected. If we assume that each SBS of $\mathcal{B}_k$ in the conflicting region acts just like a WAP, then the normalized throughput for each WAP $w \in \mathcal{W}$ according to [41] is as follows:

$$R_w^{\min} = \frac{p_{tr} p_s E[L](|\mathcal{B}_k| + 1)^{-1}}{(1 - p_{tr})T_\sigma + p_{tr} p_s T_s + p_{tr}(1 - p_s)T_c}, \tag{11}$$

where $p_{tr} = 1 - (1 - \rho)^{|\mathcal{B}_k|+1}$ is the transmission probability of at least one SBS or WAP in a time slot and ρ denotes the stationary transmission probability of APs. p_s is the successful transmission on the channel with $p_s = \frac{(|\mathcal{B}_k|+1)\tau(1-\tau)^{|\mathcal{B}_k|}}{p_{tr}}$, and $E[L]$ represents the average packet size. T_σ is the duration of an empty time slot, T_s presents the time duration of a successful transmission, and T_c illustrates the average time of a collision. Being a new-comer in the unlicensed band, SBSs should provide enough channel access opportunity to the WAP so that it can maintain a capacity between R_w^{min} and R_w^{max}.

D. PROBLEM FORMULATION

We assume that one LTE user can use one application at a time and SBSs need to share a $\tau \in [0, 1]$ time fraction with WAPs in the unlicensed spectrum. SBSs can use the rest of the time $1 - \tau$ for their users. In that case, the actual rate offered to user $j \in \mathcal{U}_i$ is as follows:

$$r_{i,j} = r_{i,j}^{l} + (1 - \tau) \cdot r_{i,j}^{u}. \tag{12}$$

Now, each SBS $i \in \mathcal{B}$ wants to maximize the sum of QoE for its users $\mathcal{U}_i$ while protecting the WAPs. The problem formulation is shown as follows:

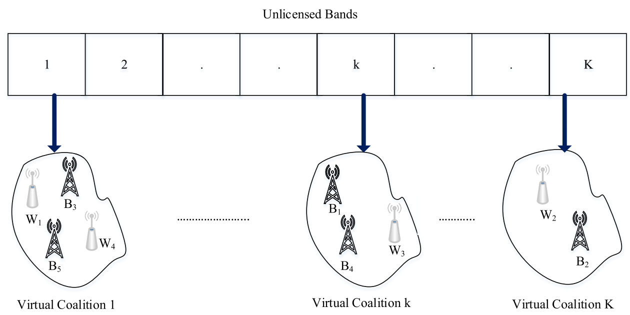

FIGURE 2. Illustration of virtual coalition formation.

$$\begin{aligned}
&\max_{\tau,\boldsymbol{\alpha}_i,\boldsymbol{\beta}_i} \sum_{j\in\mathcal{U}_i}\sum_{s\in\mathcal{S}} \lambda_{i,j}^{s}\eta_{i,j}^{s}, \quad \forall i \in \mathcal{B}\\
&\text{s.t. } C_1 : \sum_{j\in\mathcal{U}_i} \alpha_{i,j}^{p} \le 1, \quad \forall p \in \mathcal{L}_i\\
&C_2 : \sum_{p\in\mathcal{L}_i} \alpha_{i,j}^{p} \ge 1, \quad \forall j \in \mathcal{U}_i\\
&C_3 : \sum_{j\in\mathcal{U}_i} \beta_{i,j}^{q} \le 1, \quad \forall q \in \mathcal{C}_k\\
&C_4 : \sum_{j\in\mathcal{U}_i}\sum_{p\in\mathcal{L}_i} \alpha_{i,j}^{p} \le |\mathcal{L}_i|\\
&C_5 : \sum_{j\in\mathcal{U}_i}\sum_{q\in\mathcal{C}_k} \beta_{i,j}^{q} \le |\mathcal{C}_k|\\
&C_6 : \sum_{m\in\mathcal{M}} \phi_{i,j}^{m} = 1, \quad \forall j \in \mathcal{U}_i\\
&C_7 : \sum_{s\in\mathcal{S}} \lambda_{i,j}^{s} = 1, \quad \forall j \in \mathcal{U}_i\\
&C_8 : \alpha_{i,j}^{p}, \beta_{i,j}^{q}, \phi_{i,j}^{m}, \lambda_{i,j}^{s} \in \{0, 1\}, \quad \forall j, p, q, m, s\\
&C_9 : R_w^{\min} \le R_w(\tau) \le R_w^{\max}, \quad \forall w \in \mathcal{W}\\
&C_{10} : 0 \le \tau \le 1.
\end{aligned} \tag{13}$$

Here, the constraints C_1 and C_2 indicate that one licensed RB can be allocated to one user and each user should have at least one licensed RB. One unlicensed sub-carrier can also be utilized by at most one LTE user, as indicated in constraint C_3. The limitations of the total resources in the licensed and unlicensed spectra are represented by the constraints C_4 and C_5, respectively, for each SBS. The constraints C_6 and C_7 represent that each user can use one MCS and a single service at a time, respectively. Every element of $\boldsymbol{\alpha}_i$, $\boldsymbol{\beta}_i$, $\boldsymbol{\phi}_i$, and $\boldsymbol{\lambda}_i$ will be either 0 or 1, as shown in constraint C_8. The constraints C_9 and C_{10} protect the WAPs. The optimization in (13) is a Mixed Integer Non-Linear Programming (MINLP) problem, which is NP-hard due to its combinatorial properties.

IV. VIRTUAL COALITION FORMATION APPROACH

At first, each SBS needs to select an unlicensed band $k \in \mathcal{K}$ to operate. Let us assume that these sets of SBSs and WAPs, which are operating on the same unlicensed band k, form a virtual coalition (VC) $\mathcal{V}_k, \forall k \in \mathcal{K}$. Hence, $\mathcal{V}_k = \mathcal{B}_k \cup \mathcal{W}_k$, where $\mathcal{B}_k$ and $\mathcal{W}_k$ represent the sets of SBSs and WAPs, respectively, working over the unlicensed band $k \in \mathcal{K}$, $\mathcal{B} = \bigcup_{k \in \mathcal{K}} \mathcal{B}_k$, and $\mathcal{W} = \bigcup_{k \in \mathcal{K}} \mathcal{W}_k$. Three such virtual coalitions $\mathcal{V}_1, \mathcal{V}_2$, and $\mathcal{V}_3$, and a detailed working process in $\mathcal{V}_1$ are shown in Figure 1. In any coalition $\mathcal{V}_k$, $\mathcal{W}_k$ are passive members, as they are not changing their working band k, and $\mathcal{B}_k$ are active members, as they can change their working band k to join another virtual coalition. Each WAP $w \in \mathcal{W}$ is by-default a member of any $\mathcal{V}_k$ if it uses unlicensed band $k \in \mathcal{K}$. The members of each VC are also referred to as players. The decision of each $i \in \mathcal{B}$ will affect the performance of the other players in $\mathcal{V}_k$. We can easily analyze such interactions among the players $\mathcal{B}$ by using a coalition game framework [42].

A. VIRTUAL COALITION FORMATION GAME (VCFG)

SBSs want to use the unlicensed band, which is less populated. Let $\Pi = \{\mathcal{V}_1, \mathcal{V}_2, ..., \mathcal{V}_K\}$ represent a partition of $\mathcal{W}$ and $\mathcal{B}$, and we have:

$$\begin{aligned} \mathcal{V}_k \cap \mathcal{V}_{k'} &= \emptyset, \quad \forall k, k' \in \mathcal{K},\ k \neq k' \\ \cup_{k \in \mathcal{K}} \mathcal{V}_k &= \mathcal{B} \cup \mathcal{W}. \end{aligned} \tag{14}$$

Here, $\mathcal{V}_k$ is a VC consisting of a set of SBSs $\mathcal{B}_k$ and WAPs $\mathcal{W}_k$ that are using the same unlicensed band k. A coalition formation game is represented by a set of coalitions, and the coalition utility for each player is denoted by $v_i(\mathcal{V}_k, \Pi)$. More specifically, the utility value v_i is decided by two factors, namely the partition of all players Π and the coalition $\mathcal{V}_k$, where i is a member. After the formation of an initial partition Π, each player i, i.e., the active player in the coalition, can switch from coalition $\mathcal{V}_k$ to another coalition $\mathcal{V}_{k'}$, obeying the following rule:

- $v_i(\mathcal{V}_{k'}, \Pi') \succ v_i(\mathcal{V}_k, \Pi)$, i.e., player i can increase its own utility after switching to the new coalition $\mathcal{V}_{k'}$, where Π' represents the new partition when player i switches to coalition $\mathcal{V}_{k'}$.

The physical meaning of the rule is that the player i will acquire better coalition benefits after switching to the new coalition. However, the process will not guarantee the coalition utility of other already existing players in the coalition. Here, the coalition utility of player i can be defined as follows:

$$v_i(\mathcal{V}_k, \Pi) = \sum_{j \in \mathcal{U}_i} r^u_{i,j} \cdot (1 - p^u_{e,j}), \quad \forall i \in \mathcal{B}_k,\ k \in \mathcal{K}. \tag{15}$$

As per (9), the value of $p^u_{e,j}$ depends on the SINR, which is further related to other members of the coalition $\mathcal{V}_k$. Now, the coalition formation game can formally be defined as:

- Player: Each SBS $i \in \mathcal{B}$ within the considered area
- Strategy: The choice of unlicensed band from $\mathcal{K}$ by each player $i \in \mathcal{B}$
- Coalition Utility: $v_i(\mathcal{V}_k, \Pi), \forall i \in \mathcal{B}_k, k \in \mathcal{K}$.

In the following, we propose coalition switching and mutual coalition exchange rules for changing from the current coalition to a new coalition.

Definition 1 (Coalition Switch): Given a partition $\Pi = \{\mathcal{V}_1, \mathcal{V}_2, ..., \mathcal{V}_K\}$ of the set $\mathcal{B} \cup \mathcal{W}$, any SBS $i \in \mathcal{B}$ is willing to leave its current coalition $\mathcal{V}_k$ and join another coalition $\mathcal{V}_{k'}$ iff $v_i(\mathcal{V}_{k'}, \Pi') \succ v_i(\mathcal{V}_k, \Pi)$. This leads to a new partition $\Pi' = \{\Pi \setminus \{\mathcal{V}_k, \mathcal{V}_{k'}\}\} \cup \{\mathcal{V}_k \setminus \{i\}, \mathcal{V}_{k'} \cup \{i\}\}$.

Definition 2 (Coalition Preference): For any SBS $i \in \mathcal{B}$, a preference relation or order $\succeq_i$ is defined as a complete, reflexive, and transitive binary relation over the set of all coalitions in which SBS i can switch to.

Hence, for any given SBS $i \in \mathcal{B}$, $\mathcal{V}_{k'} \succeq_i \mathcal{V}_{k''}$, implies that SBS i prefers to join $\mathcal{V}_{k'}$ over the coalition $\mathcal{V}_{k''}$, or at least, i prefers both coalitions $\mathcal{V}_{k'}$ and $\mathcal{V}_{k''}$ equally. On the other hand, $\mathcal{V}_{k'} \succ_i \mathcal{V}_{k''}$ implies that SBS i strictly prefers $\mathcal{V}_{k'}$ over $\mathcal{V}_{k''}$. In our case, $\mathcal{V}_{k'} \succeq_i \mathcal{V}_{k''}$ indicates that SBS i can obtain better or at least equal coalition value when it switches to $\mathcal{V}_{k'}$ rather than $\mathcal{V}_{k''}$ from its current coalition $\mathcal{V}_k$.

Therefore, SBS $i \in \mathcal{B}$ can leave its current coalition $\mathcal{V}_k$ and join another coalition $\mathcal{V}_{k'}$ by using the switch operation for a given partition Π. Here, $\mathcal{V}_{k'}$ is the most preferred coalition of SBS i in current partition Π, as defined by Definition 2. Therefore, the switch operation will strictly improve the coalition utility of the SBS i without considering others coalition utilities. Besides, whenever an SBS chooses to switch to a new coalition, it updates its history set h^s. Thus, for a given partition Π, if an SBS $i \in \mathcal{V}_k$ decides to leave its current coalition and join another coalition $\mathcal{V}_{k'}$, then SBS i will update h^s_i by adding $\mathcal{V}_k$.

Definition 3 (Mutual Coalition Exchange): Given a partition $\Pi = \{\mathcal{V}_1, \mathcal{V}_2, ..., \mathcal{V}_K\}$ of the set $\mathcal{B} \cup \mathcal{W}$, the coalition exchange can be defined as follows: two players $i \in \mathcal{V}_k$, $i' \in \mathcal{V}_{k'}$, and $i, i' \in \mathcal{B}$ with current coalition utility $v_i(\mathcal{V}_k, \Pi)$ and $v_{i'}(\mathcal{V}_{k'}, \Pi)$, respectively, want to mutually switch their coalitions, which leads to a new partition $\Pi' = \{\Pi \setminus \{\mathcal{V}_k, \mathcal{V}_{k'}\}\} \cup \{\mathcal{V}_k \setminus \{i\} \cup \{i'\}, \mathcal{V}_{k'} \setminus \{i'\} \cup \{i\}\}$ when the following conditions hold:

$$\begin{aligned} v_i(\mathcal{V}_{k'}, \Pi') &> v_i(\mathcal{V}_k, \Pi) \\ v_{i'}(\mathcal{V}_k, \Pi) &= v_{i'}(\mathcal{V}_{k'}, \Pi) \end{aligned} \tag{16}$$

or

$$\begin{aligned} v_i(\mathcal{V}_{k'}, \Pi') &= v_i(\mathcal{V}_k, \Pi) \\ v_{i'}(\mathcal{V}_k, \Pi) &> v_{i'}(\mathcal{V}_{k'}, \Pi). \end{aligned} \tag{17}$$

Definition 3 ensures that any mutual exchange of coalitions between the pair will increase the coalition utility of one player without affecting the utilities of the others. Hence, the exchange will increase the total system utility. Therefore, if there are two players $i \in \mathcal{V}_k$ and $i' \in \mathcal{V}_{k'}$ for a given partition Π that want to exchange their current coalitions, then either v_i will increase and $v_{i'}$ will be unchanged, or $v_{i'}$ will increase and v_i will be unchanged in the new coalitions. In this case, both the players will update their exchange histories h^e_i and $h^e_{i'}$ by storing $\mathcal{V}_k$ and $\mathcal{V}_{k'}$ respectively.

B. VCFG ALGORITHM

The coalition formation game, shown in Algorithm 1 mainly consists of two phases. The first phase is based on Definition 1 and the second phase is based on Definition 3.

Algorithm 1 Coalition Formation Game Algorithm

Input: The SBSs $\mathcal{B}$ and WAPs $\mathcal{W}$ in the network choose the unlicensed band randomly from $\mathcal{K}$ and form an initial partition $\Pi_0 = \{\mathcal{V}_1, \mathcal{V}_2, ..., \mathcal{V}_K\}$.
Output: Π_f^*
PhaseI : *CoalitionSwitch*
Set current partition $\Pi_c = \Pi_0$
repeat
  for every SBS $i \in \mathcal{B}$, given any current partion Π_c **do**
    SBS i calculates its current coalition value $v_i(\mathcal{V}_k, \Pi_c)$ and prospective coalition value $v_i(\mathcal{V}_{k'}, \Pi_c')$ if it switches to another coalition $k' \neq k$ to form new partition Π_c', $\forall k' \in \mathcal{K}$ by using (15).
    SBS i chooses k' from the top of its preference order considering h_i^s
    if such k' exists **then**
      Update $h_i^s = h_i^s \cup \{k\}$
      Update $\Pi_c = \{\Pi_c \backslash \{\mathcal{V}_k, \mathcal{V}_{k'}\}\} \cup \{\mathcal{V}_k \backslash \{i\}, \mathcal{V}_{k'} \cup \{i\}\}$
    end if
  end for
until Convergence to the Nash-stable partition $\Pi_f = \Pi_c$

PhaseII : *MutualCoalitionExchange*
Set $\Pi_f^* = \Pi_f$
repeat
  if there is a pair of SBSs $(i \in \mathcal{V}_k, i' \in \mathcal{V}_{k'})$ in Π_f such that either (16) or (17) are satisfied **then**
    Update $h_i^e = h_i^e \cup \{k\}$
    Update $h_{i'}^e = h_{i'}^e \cup \{k'\}$
    $\Pi_f^* = \{\Pi_f^* \backslash \{\mathcal{V}_k, \mathcal{V}_{k'}\}\} \cup \{\mathcal{V}_k \backslash \{i\} \cup \{i'\}, \mathcal{V}_{k'} \backslash \{i'\} \cup \{i\}\}$
  end if
until there is no such SBS pair

- Phase I: Each SBS $i \in \mathcal{B}$ individually makes the decision to switch coalitions based on the preference order of Definition 2 and switching history h_i^s without relying on any coordination mechanism. h_i^s forbids SBS $i \in \mathcal{B}$ to switch to the same coalition again. This process continues until it converges to the Nash-stable partition Π_f.
- Phase II: The SBSs can further increase their coalition utility via coordination mechanisms by exchanging coalitions mutually. Here, each SBS $i \in \mathcal{B}$ maintains a history of the coalition exchange h_i^e to stop infinite race among the SBSs. This process continues until there is a pair of interested SBSs.

The stability of the final partition can be studied using the following individual stability and Nash stability concepts of [43].

Definition 4 (Individual Stability): A partition $\Pi = \{\mathcal{V}_1, \mathcal{V}_2, ..., \mathcal{V}_K\}$ is individually stable if $\nexists i \in \mathcal{B}$ and coalition $\mathcal{V}_{k'} \in \Pi \cup \{\emptyset\}$ such that $\mathcal{V}_{k'} \cup \{i\} \succ_i \mathcal{V}_k$, where $i \in \mathcal{V}_k$.

Definition 5 (Nash Stability): A partition $\Pi = \{\mathcal{V}_1, \mathcal{V}_2, ..., \mathcal{V}_K\}$ is Nash-stable if $\mathcal{V}_k \succ_i \mathcal{V}_{k'} \cup \{i\}$, $\forall i \in \mathcal{B}$, where $i \in \mathcal{V}_k$ and $\forall \mathcal{V}_{k'} \in \Pi \cup \{\emptyset\}$.

Theorem 1: Algorithm 1 produces a stable partition after a finite number of switch and exchange operations.

Proof: Let Π_0 be the initial partition of the SBSs and WAPs. The first phase of the proposed coalition formation algorithm consists of a sequence of switch operations with the initialization of $\Pi_c = \Pi_0$. According to Definition 1, every switch operation transforms the current partition Π_c into another partition Π_c' and hence yields the following chain of transformations:

$$\Pi_c^0 \rightarrow \Pi_c^1 \rightarrow \Pi_c^2 \rightarrow \cdots \rightarrow \Pi_c^m \rightarrow \cdots \rightarrow \Pi_c^n \rightarrow \cdots, \tag{18}$$

where $\rightarrow$ indicates a switch operation. Every switch operation of any SBS $i \in \mathcal{B}$ follows its preference order and switch history h_i^s, leading to a new partition. As there are $|\mathcal{K}|$ coalitions in any partition, the number of switch operations for any SBS is limited. A switching history is used to ensure a new partition for every switch operation. Thus, the number of partitions of a set is finite and given by the Bell number [44], and so the number of transformations in (18) is finite. Hence, the sequence in (18) will converge to a final partition Π_f after a finite number of steps.

Now, assume that the partition Π_f is not Nash-stable. That means $\exists i \in \mathcal{B}$ and a coalition $\mathcal{V}_{k'} \in \Pi_f$ such that $\mathcal{V}_{k'} \cup \{i\} \succ_i \mathcal{V}_k$, where $i \in \mathcal{V}_k$. Hence, SBS i can perform a switch operation to join coalition $\mathcal{V}_{k'}$, which contradicts the fact that Π_f is the converged output of the first phase of the proposed algorithm. Thus, Π_f is Nash-stable and hence, by Bogomonlaia and Jackson [43], Π_f is also individually stable. Hence, Phase I of Algorithm 1 converges to a stable partition Π_f.

The second phase of Algorithm 1, consists of a sequence of mutual exchange operations among the SBSs via some coordination mechanism. This phase starts with the result of the first phase. Such an exchange operation is strictly beneficial to one member of the pair (the benefit of another member is unchanged) without affecting the stability notation of the partition, thus forming a new partition Π_f^*. The number of exchange operations will be finite for a finite number of SBSs and coalitions. This phase is also restricted by using exchange history. Hence, Phase II will produce a stable partition Π_f^* after a finite number of exchange operations. Therefore, Algorithm 1 converges to a stable partition Π_f^*. ■

V. DECOMPOSITION OF THE PROBLEM FOR SOLVING WITH KALAI-SMORODINSKY BARGAINING SOLUTION AND Q-LEARNING

After forming the partition Π_f^*, the problem of a particular SBS $i \in \mathcal{B}$ is now confined within a particular coalition $\mathcal{V}_k \in \Pi_f^*$, where $i \in \mathcal{V}_k$. As shown in Figure 1, each Wi-Fi user is affected by all $|\mathcal{B}_k|$ SBSs, whereas each LTE user is affected by $|\mathcal{B}_k| - 1$ SBSs and one WAP (if the LTE user is under the coverage area of that WAP) inside the coalition $\mathcal{V}_k$ in the unlicensed spectrum. However, Cavalcante *et al.* [45] show that WAP has negligible impact on LTE performance in the unlicensed spectrum. Thus, we can ignore the negative impact of WAP on LTE users. Now, the optimization problem is expressed as follows:

$$\begin{aligned} \max_{\tau_k,\boldsymbol{\alpha}_i,\boldsymbol{\beta}_i} & \sum_{j\in\mathcal{U}_i}\sum_{s\in\mathcal{S}} \lambda_{i,j}^s \eta_{i,j}^s, \quad \forall i \in \mathcal{B}_k, \forall k \in \mathcal{K} \\ \text{s.t. } & C_1, \ldots, C_8 \\ & C_9 : R_w^{\min} \le R_w(\tau_k) \le R_w^{\max}, \quad \forall w \in \mathcal{W}_k \\ & C_{10} : 0 \le \tau_k \le 1, \quad \forall w \in \mathcal{W}_k. \end{aligned} \tag{19}$$

Hence, every SBS wants to maximize the MOS value considering the constraints inside the coalition, and the SBSs will follow the procedure described in Theorem 2.

Theorem 2: The SBSs in coalition $\mathcal{V}_k$ will split $\mathcal{C}_k$ orthogonally to obtain the maximum benefits from the unlicensed spectrum band $k \in \mathcal{K}$.

Proof: The SINR of any user $j \in \mathcal{U}_i$ associated with SBS $i \in \mathcal{B}_k$ within coalition $\mathcal{V}_k$ without considering the WAP's effect in the unlicensed resource $q \in \mathcal{C}_k$ is represented as follows:

$$\gamma_{i,j}^q = \frac{\beta_{i,j}^q P_i^u |h_{i,j}|^2}{\sum_{i'\in\mathcal{B}_k, i'\neq i}\sum_{j'\in U_{i'}} \beta_{i',j'}^q P_{i'}^u |h_{i',j}|^2 + \sigma^2}. \tag{20}$$

As the SBSs and LTE-U users are distributed randomly in a small conflicting area, the received signal of any user from any SBS in any unlicensed resource is almost the same. Let this received signal be Δ regardless of the resource, the user and SBS inside the coalition. Then, the SINR is expressed as follows:

$$\gamma_1^q = \frac{\Delta}{(|\mathcal{B}_k|-1)\Delta + \sigma^2} = \frac{1}{(|\mathcal{B}_k|-1) + \frac{\sigma^2}{\Delta}}. \tag{21}$$

If $|\mathcal{B}_k|$ is sufficiently large, then $\gamma_1^q \approx 0$. The received rate in this case for any user in unlicensed resource $q \in \mathcal{C}_k$ is defined as follows:

$$R_1^q = r(1 - p_{e,1}^q) \approx 0. \tag{22}$$

Hence, the received rate by the user in any unlicensed resource $q \in \mathcal{C}_k$ is close to zero. This means that it will not provide any benefit to the system and the total sum-rate of the users is approximately zero in the unlicensed band $k \in \mathcal{K}$. Thus, the SBSs should cooperate to utilize the unlicensed spectrum. If two SBSs in the coalition $\mathcal{V}_k$ cooperate, then their users will experience interference from the rest of the SBSs that are using the same resource. In that case, the perceived SINR of a user in the coalition is defined as follows:

$$\gamma_2^q = \frac{\Delta}{(|\mathcal{B}_k|-2)\Delta + \sigma^2} = \frac{1}{(|\mathcal{B}_k|-2) + \frac{\sigma^2}{\Delta}}. \tag{23}$$

Following the same process, if $3, \ldots, (|\mathcal{B}_k|-1), |\mathcal{B}_k|$ SBSs form a coalition, then the SINRs are as follows:

$$\begin{aligned} \gamma_3^q &= \frac{\Delta}{(|\mathcal{B}_k|-3)\Delta + \sigma^2} = \frac{1}{(|\mathcal{B}_k|-3) + \frac{\sigma^2}{\Delta}} \\ \gamma_{|\mathcal{B}_k|-2}^q &= \frac{\Delta}{\Delta + \sigma^2} = \frac{1}{2 + \frac{\sigma^2}{\Delta}} \\ \gamma_{|\mathcal{B}_k|-1}^q &= \frac{\Delta}{\Delta + \sigma^2} = \frac{1}{1 + \frac{\sigma^2}{\Delta}} \\ \gamma_{|\mathcal{B}_k|}^q &= \frac{\Delta}{\sigma^2}. \end{aligned} \tag{24}$$

The values of $\gamma_2^q, \gamma_3^q, \ldots, \gamma_{|\mathcal{B}_k|-1}^q$ will be maximal when $\frac{\sigma^2}{\Delta} \to 0$, i.e., $\Delta \gg \sigma^2$. In that case, the SINRs will be $\gamma_2^q = \frac{1}{|\mathcal{B}_k|-2}, \gamma_3^q = \frac{1}{|\mathcal{B}_k|-3}, \ldots$, and $\gamma_{|\mathcal{B}_k|-1}^q = 1$ respectively. When $|\mathcal{B}_k|$ is sufficiently large, the value of $\gamma_2^q, \gamma_3^q \approx 0$ and the received rate from a particular resource is also approximately zero. That means the sum-rate of these cases are close to zero.

We want to investigate the last three scenarios. If $|\mathcal{B}_k|-2$, $|\mathcal{B}_k|-1$ and $|\mathcal{B}_k|$ SBSs cooperate with each other and use orthogonal resources, then $\gamma_{|\mathcal{B}_k|-2}^q = \frac{1}{2}, \gamma_{|\mathcal{B}_k|-1} = 1$, and $\gamma_{|\mathcal{B}_k|} = \frac{\Delta}{\sigma^2} \gg 1$. Thus, the received rates in the particular resource q for these three scenarios are as follows:

$$\begin{aligned} R_{|\mathcal{B}_k|-2}^q &= 3r(1 - p_{e,|\mathcal{B}_k|-2}^q) \\ R_{|\mathcal{B}_k|-1}^q &= 2r(1 - p_{e,|\mathcal{B}_k|-1}^q) \\ R_{|\mathcal{B}_k|}^q &= r(1 - p_{e,|\mathcal{B}_k|}^q). \end{aligned} \tag{25}$$

If we substitute the values of $\gamma_{|\mathcal{B}_k|-2}^q, \gamma_{|\mathcal{B}_k|-1}^q$, and $\gamma_{|\mathcal{B}_k|}^q$ in (9) keeping all other parameters unchanged, then we get the value of $p_{e,|\mathcal{B}_k|-2}^q, p_{e,|\mathcal{B}_k|-1}^q$, and $p_{e,|\mathcal{B}_k|}^q$ in such a way that $R_{|\mathcal{B}_k|}^q > R_{|\mathcal{B}_k|-1}^q > R_{|\mathcal{B}_k|-2}^q$, according to (25). Therefore, SBSs in coalition $\mathcal{V}_k$ will split $\mathcal{C}_k$ orthogonally to obtain the maximum benefits from the unlicensed band $k \in \mathcal{K}$. ■

Now, our goal is to split resource $\mathcal{C}_k$ among the SBSs $\mathcal{B}_k$ in such a way that $\mathcal{C}_k = \mathcal{C}_k^1 \cup \mathcal{C}_k^2 \cup \cdots \cup \mathcal{C}_k^{|\mathcal{B}_k|}$ and $\mathcal{C}_k^i \cap \mathcal{C}_k^{i'} = \emptyset, \forall i, i' \in \mathcal{B}_k$ and $i \neq i'$. Division of the resource should be fair among the SBSs. Hence, we use the BG [46] to solve this problem. The standard BG consists of a set of agents $\mathcal{A}$, an amount of money M, and a claim vector $\boldsymbol{d}$ with $\sum_{a\in\mathcal{A}} d_a \ge M$. If $\boldsymbol{x}$ represents a solution of this BG, then it must satisfy the following conditions:

$$\begin{aligned} 0 \le x_a \le d_a, &\quad \forall a \in \mathcal{A} \\ \sum_{a\in\mathcal{A}} x_a = M. & \end{aligned} \tag{26}$$

We have a set of SBSs $\mathcal{B}_k$ as the agents, an amount of unlicensed resource $|\mathcal{C}_k|$ as the money, and requirements on the resources of each SBS as the claims in our $\mathcal{V}_k$. Algorithm 2 is used to distribute the resource among the SBSs inside $\mathcal{V}_k$.

Hence, the optimization problem in (19) can be rewritten for each SBS $i \in \mathcal{B}_k$ based on C_k^i as follows:

$$\begin{aligned} \max_{\tau_k,\boldsymbol{\alpha}_i,\boldsymbol{\beta}_i} & \sum_{j\in\mathcal{U}_i}\sum_{s\in\mathcal{S}} \lambda_{i,j}^s \eta_{i,j}^s, \quad \forall i \in \mathcal{B}_k, \ \forall k \in \mathcal{K} \\ \text{s.t. } & C_1, \ C_2, \ C_4, \ C_6, \ C_7, \ C_8 \\ & C_3 : \sum_{j\in\mathcal{U}_i} \beta_{i,j}^q \le 1, \quad \forall q \in C_k^i \\ & C_5 : \sum_{j\in\mathcal{U}_i}\sum_{q\in C_k^i} \beta_{i,j}^q \le |C_k^i| \\ & C_9 : R_w^{\min} \le R_w(\tau_k) \le R_w^{\max}, \quad \forall w \in \mathcal{W}_k \\ & C_{10} : 0 \le \tau_k \le 1, \quad \forall w \in \mathcal{W}_k. \end{aligned} \tag{27}$$

Algorithm 2 Split of $\mathcal{C}_k$ Among SBSs $\mathcal{B}_k$

Input: $\mathcal{B}_k, \mathcal{C}_k$
Output: $\mathcal{C}_k^i, \forall i \in \mathcal{B}_k$
Initialization: $\mathcal{C}_k^i = \emptyset, \forall i \in \mathcal{B}_k$
for each SBS $i \in \mathcal{B}_k$ **do**
  SBS i determines its claim d_i depending on $\mathcal{U}_i$ and $\mathcal{L}_i$ and sends to the coordinator
end for
for each SBS $i \in \mathcal{B}_k$ **do**
  $J_k^i = \frac{d_i}{\sum_{i' \in \mathcal{B}_k} d_{i'}} \cdot |\mathcal{C}_k|$
  for $q = 1$ to J_k^i **do**
    $\mathcal{C}_k^i = \mathcal{C}_k^i \cup \{q\}$
  end for
end for
Arbitrator sends $\mathcal{C}_k^i$ to each $i \in \mathcal{B}_k$

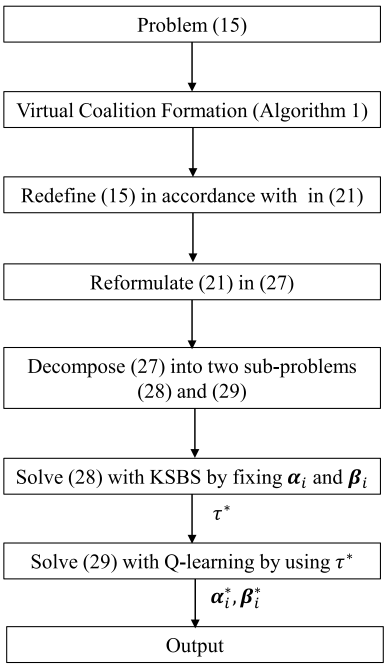

FIGURE 3. Solution of the problem.

Now, we want to decompose the problem in (27) for each SBS $i \in \mathcal{B}_k$ into two sub-problems so that each of them can be solved with a suitable technique. The overall solution process of the problem is shown in Figure 3. First, with fixed resource allocation, the time sharing problem between $\mathcal{B}_k$ and $\mathcal{W}_k$ in $\mathcal{V}_k$ can be represented as follows:

$$\max_{\tau_k} U_i(\tau_k, \boldsymbol{\alpha}_i, \boldsymbol{\beta}_i) = \sum_{j \in \mathcal{U}_i} \sum_{s \in \mathcal{S}} \lambda_{i,j}^s \eta_{i,j}^s, \quad \forall i \in \mathcal{B}_k$$
$$\text{s.t. } C_9, C_{10}. \tag{28}$$

Second, with fixed τ_k (obtained from (28)), the licensed and unlicensed resources should be allocated to the users so that the objective function in (27) can be maximized under the constraints as follows:

$$\max_{\boldsymbol{\alpha}_i, \boldsymbol{\beta}_i} U_i(\tau_k, \boldsymbol{\alpha}_i, \boldsymbol{\beta}_i) = \sum_{j \in \mathcal{U}_i} \sum_{s \in \mathcal{S}} \lambda_{i,j}^s \eta_{i,j}^s, \quad \forall i \in \mathcal{B}_k$$
$$\text{s.t. } C_1, \ldots, C_8. \tag{29}$$

The sub-problems in (28) and (29) have the same goal with different constraints and are connected through the parameters τ_k, $\boldsymbol{\alpha}_i$, and $\boldsymbol{\beta}_i$. The solution of the sub-problem in (28) is used to solve the sub-problem in (29), and we can obtain the solution of the original problem.

A. SOLUTION OF SUB-PROBLEM (28) USING THE KALAI-SMORODINSKY BARGAINING SOLUTION

From (28), if every SBS $i \in \mathcal{B}_k$ wants to maximize $U_i(\tau_k, \boldsymbol{\alpha}_i, \boldsymbol{\beta}_i)$, then they will provide a minimum τ_0 for maintaining $R_w^{min}, \forall w \in \mathcal{W}_k$. This can be detrimental to the performance of the WAPs $\mathcal{W}_k$ due to the non-coordination among SBSs. Hence, we require coordination among the SBSs to determine a win-win strategy for the effective coexistence between $\mathcal{B}_k$ and $\mathcal{W}_k$. Thus with fixed $\boldsymbol{\alpha}_i$ and $\boldsymbol{\beta}_i$ for every $i \in \mathcal{B}_k$, we reformulate the problem in (28) as follows:

$$\max_{\tau_k} U_{\mathcal{B}_k}(\tau, \boldsymbol{\alpha}, \boldsymbol{\beta}) = \sum_{i \in \mathcal{B}_k} \sum_{j \in \mathcal{U}_i} \sum_{s \in \mathcal{S}} \lambda_{i,j}^s r_{i,j}^u (1 - p_{e,j}^u)$$
$$\text{s.t. } \tau_k^0 \cdot R_w^{max} \le R_w(\tau_k) \le R_w^{max} \tag{30}$$

where $\tau_k^0 = f(\mathcal{B}_k, \mathcal{W}_k) = \frac{R_w^{min}}{R_w^{max}} \in [0, 1]$ is the channel access time of a WAP if all the members of $\mathcal{V}_k$ act as WAPs.

To solve this *coopetition* for resources among the players, the bargaining solution is used as fairness criteria, and the Nash bargaining solution (NBS) [47] is the most used approach in the wireless industry. However, NBS focuses on common goal maximization, which is not desirable among selfish players. On the other hand, a possible desired fairness policy might ensure the same utility penalty for every player in the case of *coopetition*, and the Kalai-Smorodinsky bargaining solution (KSBS) [48] is a good candidate for achieving fairness. Moreover, KSBS provides a utility that is proportional to the achievable maximum utility and guarantees a Pareto optimal utility. Recently, KSBS has been used in many application areas such as data center network (for distributing computing resources) [49], OFDM communications (for maintaining trade-off between secrecy and throughput) [50], smart grid communications (for payoff allocation) [51] etc. in cooperative fashion. Thus, we can use cooperative KSBS for distributing our resource, time, effectively among the competitors. A solution concept $\boldsymbol{u}^* = F(\boldsymbol{U}, \boldsymbol{d})$ is said to be the KSBS if it has individual rationality, feasibility, pareto optimality, individual monotonicity, independent of linear transformation and symmetry properties, where $\boldsymbol{U}$ represents the feasible set with each element $\boldsymbol{u} = [u_1, u_2, \ldots, u_N]^T \in \boldsymbol{U}$, and $\boldsymbol{d} = [d_1, d_2, \ldots, d_N]$ represents the disagreement point of the competitors. The solution $\boldsymbol{u}^* = [u_1^*, u_2^*, \ldots, u_N^*]^T$ is unique and satisfies the following:

$$\frac{u_1^* - d_1}{u_1^{max} - d_1} = \frac{u_2^* - d_2}{u_2^{max} - d_2} = \cdots = \frac{u_N^* - d_N}{u_N^{max} - d_N}, \tag{31}$$

where u_i^{max} is the maximum possible utility of player i when it uses all of the resources. In our *coopetition*, $\mathcal{B}_k$ and $\mathcal{W}_k$ act as two players in band $k \in \mathcal{K}$, and $\mathcal{B}_k$ should provide access opportunities to the band at least by time τ_0 for $\mathcal{W}_k$. The disagreement value for $\mathcal{B}_k$ is $d_{\mathcal{B}_k} = 0$, as they want to protect incumbent $\mathcal{W}_k$. Hence, we can redefine the problem in (30) using KSBS as follows:

$$\max_{\tau_k^*} U^*_{\mathcal{B}_k}(\tau_k^*, \boldsymbol{\alpha}, \boldsymbol{\beta})$$
$$\text{s.t. } \frac{U^*_{\mathcal{B}_k}}{U^{max}_{\mathcal{B}_k}} = \frac{U^*_{\mathcal{W}_k} - d_{\mathcal{W}_k}}{U^{max}_{\mathcal{W}_k} - d_{\mathcal{W}_k}}. \quad (32)$$

Theorem 3: The coexistence in $\mathcal{V}_k$ is defined by the optimal sharing fraction $\tau_k^* = \frac{1}{2-\tau_k^0}$.

Proof: Let $\mathcal{B}_k$ share $\tau_k \in [\tau_k^0, 1]$ with $\mathcal{W}_k$ in $\mathcal{V}_k$. Now from the constraint of (32), we obtain the following expression:

$$\frac{(1-\tau_k)\cdot U^{max}_{\mathcal{B}_k}}{U^{max}_{\mathcal{B}_k}} = \frac{\tau_k \cdot R^{max}_{\mathcal{W}_k} - \tau_k^0 \cdot R^{max}_{\mathcal{W}_k}}{R^{max}_{\mathcal{W}_k} - \tau_k^0 \cdot R^{max}_{\mathcal{W}_k}} \quad (33)$$

$$1-\tau_k = \frac{\tau_k - \tau_k^0}{1-\tau_k^0} \quad (34)$$

$$(1-\tau_k)(1-\tau_k^0) = \tau_k - \tau_k^0. \quad (35)$$

After simplifying (35), we obtain the value of τ as follows:

$$\tau_k = \frac{1}{2-\tau_k^0}. \quad (36)$$

Now, let $\tau_k = f(\tau_k^0) = \frac{1}{2-\tau_k^0}$ and determine the behavior of (36) using derivatives as follows:

$$f'(\tau_k^0) = \frac{1}{(2-\tau_k^0)^2}$$
$$f''(\tau_k^0) = \frac{2}{(2-\tau_k^0)^3}. \quad (37)$$

As the value of $\tau_k^0 \in [0, 1]$, we obtain $f'(\tau_k^0) > 0$ and $f''(\tau_k^0) > 0$ from (37). This means that (36) is a convex function of τ_0 and hence, the fair coexistence between $\mathcal{B}_k$ and $\mathcal{W}_k$ in $\mathcal{V}_k$ occurs when $\tau_k^* = \frac{1}{2-\tau_k^0}$. ∎

B. SOLUTION OF SUB-PROBLEM (29) USING Q-LEARNING

In this section, we propose a reinforcement learning (RL) approach for resource allocation based on the Q-learning framework. RL is a model-free learning technique, and requires less computation and space, which is then used as an approximation method to solve the NP-hard problem (29). The stochastic optimal policy is learned from the interactions with the environment in the case of RL. RL tries to map environment states (s) to optimal actions (a) via trial-and-error experiences to maximize the sum of accumulated reward [52]. RL algorithms try to estimate $Q(\mathsf{s}, \mathsf{a})$, $\forall \mathsf{s}, \mathsf{a}$, and store them in an array called a Q-table. A one-dimensional Q-table $Q(\mathsf{a})$ can be considered for every action a in a stateless environment [53]. In that case, a learning agent aims to predict an expected value as a reward for each action available. Q-learning is one of the most widely used RL algorithms for resource sharing in the cellular system, e.g., [18], [19], [54], [55]. Our stateless Q-learning model is formally defined as follows:

- *Agent*: Each SBS $i \in \mathcal{B}_k, \forall k \in \mathcal{K}$.
- *Actions*: $\mathcal{A}_i = [\mathsf{a}_i^1, \mathsf{a}_i^2, \ldots, \mathsf{a}_i^N]$ represents all the resource allocation schemes that SBS i can take considering its users $\mathcal{U}_i$ with their associated services. Here, each vector a_i^n shows an action n which consists of the resource allocation pair $(\boldsymbol{\alpha}_i, \boldsymbol{\beta}_i)$ for all its users, and N is the possible number of actions.
- *Reward*: $\Re_i = [\mathsf{r}_i^1, \mathsf{r}_i^2, \ldots, \mathsf{r}_i^N]^T$ represents the set of rewards that SBS i can achieve for the actions $\mathcal{A}_i$. Here, each component r_i^n indicates the reward for action a_i^n, and more specifically the value of this reward is as follows:

$$\mathsf{r}_i^n = U_i(\tau^*, \mathsf{a}_i^n). \quad (38)$$

To assess the allocation schemes comprehensively, each SBS i maintains a Q-table Q_i^n based on the reward r_i^n such that every allocation scheme n (i.e., action a_i^n) has a Q-value associated with it. The SBS i can allocate resources to the user until there are no unused resources in $\mathcal{L}_i$ and $\mathcal{C}_k^i$, considering the constraints of (29). The SBS decides the allocation scheme depending upon the current Q-table, and the greedy action selection strategy is explained as follows:

$$\hat{n} = \underset{n}{\text{argmax}}(Q_i^n), \quad (39)$$

where $\hat{n}$ is the allocation scheme chosen and Q_i^n is the Q-value of the n^{th} allocation scheme, i.e., a_i^n.

Initially, all the values of the Q-table are zero, and hence, the SBS begins learning with equal opportunities from all possible actions. SBS i updates the Q-table Q_i^n every time it attempts to use action a_i^n in the form of reward r_i^n. A recursive equation for updating the Q-value for stateless Q-learning, as defined in [53], is shown as follows:

$$Q_i^n \leftarrow \vartheta \mathsf{r}_i^n + (1-\vartheta) Q_i^n, \quad \forall \mathsf{a}_i^n \in \mathcal{A}_i, \quad (40)$$

where Q_i^n represents the Q-value of the n^{th} action, r_i^n is the reward associated with action a_i^n for the most recent trail, and $\vartheta \in [0, 1]$ is the learning rate parameter. ϑ creates a balance between recent experience and previous estimates of the Q-values. Q-learning will converge to the exact Q-values for every possible action in the single agent framework if ϑ discounts slowly during the learning period and all actions are inspected indefinitely [56]. The major difference between our model and the Q-learning based coexistence models [18], [19] is the utilization of the state space. It is very challenging to determine the real-time state space in such a versatile environment.

SBSs can use the ϵ-greedy mechanism for selecting actions. By using this mechanism, SBS can increase the probability of selecting an optimal action and meanwhile, choose other actions with non-zero probability. Thus, the SBS chooses a non-optimal action with probability ϵ (known as the exploration step) and an optimal action with probability $1-\epsilon$ (known as the exploitation step). The SBS can choose non-optimal actions uniformly or based on the Q-values from the exploration phase. *Boltzmann exploration* is a popular biased strategy where action $n \neq \hat{n}$ is chosen with probability $\frac{e^{\frac{Q_i^n}{T}}}{\sum_{n',n'\neq\hat{n}} e^{\frac{Q_i^{n'}}{T}}}$. Here, the temperature parameter is $T > 0$ and can be decreased over time, and hence, the exploitation probability increases. Algorithm 3 shows the Q-learning based resource allocation process of SBS $i \in \mathcal{B}$. The convergence of Algorithm 3 is shown in the Figure 4. The figure shows that the algorithm converges within 400 $\sim$ 500 iterations with respect to total and average Q-value.

Algorithm 3 Q-Learning Based Resource Allocation Algorithm for SBS i

Input: Set of actions $\mathcal{A}_i$ and τ_k^*
Output: $\boldsymbol{\alpha}_i, \boldsymbol{\beta}_i$
Initialization: Q-value for SBS i: $Q_i^n = 0, \forall \mathsf{a}_i^n \in \mathcal{A}_i$
for time t **do**
  if $rand(\cdot) \leq \epsilon$ **then**
    Choose action a_i^n with probability $\frac{e^{\frac{Q_i^n}{T}}}{\sum_{n',n'\neq\hat{n}} e^{\frac{Q_i^{n'}}{T}}} \cdot \epsilon$
  else
    Choose action $\mathsf{a}_i^{\hat{n}} = \text{argmax}_{\mathsf{a}_i^n}(\mathsf{r}_i^n)$
  end if
  Update $Q_i^m \leftarrow \vartheta \mathsf{r}_i^m + (1-\vartheta) Q_i^m$ where $m \in \{\mathsf{a}_i^{\hat{n}}, \mathsf{a}_i^n\}$ depending upon the chosen action
end for
SBS i finds optimal allocation scheme $\mathsf{a}_i^* \equiv (\boldsymbol{\alpha}_i^*, \boldsymbol{\beta}_i^*)$ by comparing the Q-values

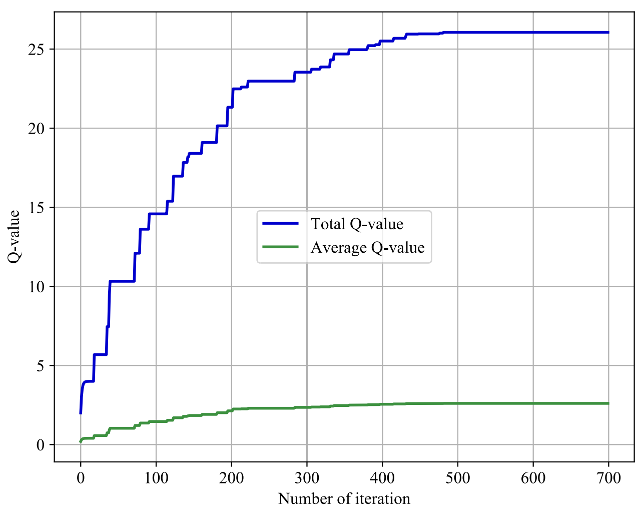

FIGURE 4. Convergence analysis of Algo. 3.

C. QOE MAXIMIZATION FOR LTE-U COEXISTENCE

The overall QoE maximization process for each SBS is shown in Algorithm 4. Each SBS obtains the optimal τ_k^*

Algorithm 4 Maximization of QoE for LTE-U Network

1: **Input**: Π_f^*
2: **Output**: $\boldsymbol{\eta}_i, \forall i \in \mathcal{B}$
3: Arbitrator determines τ_k^* for each $\mathcal{V}_k$ by using Theorem 3 and informs it to every $i \in \mathcal{B}_k$
4: Each SBS $i \in \mathcal{B}_k$ determines $(\boldsymbol{\alpha}_i^*, \boldsymbol{\beta}_i^*)$ by using Algorithm 3
5: Each SBS $i \in \mathcal{B}_k$ determines $\eta_{i,j}^s, \forall j \in \mathcal{U}_i$ by using τ_k^*, $\boldsymbol{\alpha}_i^*$, and $\boldsymbol{\beta}_i^*$

(shown in line 3) from the arbitrator, which defines the coexistence between LTE-U SBSs and WAPs inside each coalition. Then, each SBS allocates the licensed and unlicensed resources to maximize the objective function (shown in line 4).

D. COMPLEXITY ANALYSIS

Our proposed method mainly consists of three mechanisms namely (i) VCF, (ii) Time sharing, and (iii) Resource allocation. VCF process is represented in Algo. 1 which comprises of switch and exchange steps. In our model, we have $|\mathcal{K}|$ coalitions where $|\mathcal{B}|$ SBSs can join. In a worst case, a SBS $i \in \mathcal{B}$ can switch from its' current coalition to any one from the rest of $|\mathcal{K}|-1$ coalitions. Thus, the total worst case witch form step I of Algo. 1 can be $|\mathcal{B}| \cdot (|\mathcal{K}|-1)$. After forming a Nash-stable partition Π_f in the phase I of Algo. 1, there will be a few SBSs who are interested in mutual coalition exchange operation of phase II of Algo. 1. If $\mathcal{B}'$ represents the set of SBSs that are interested in such operation where $|\mathcal{B}'| \ll |\mathcal{B}|$, then the worst case complexity of phase II can be $\frac{|\mathcal{B}'|(|\mathcal{B}'|-1)}{2}$. Thus, the total worst case complexity of Algo. 1 is $\mathcal{O}\big(|\mathcal{B}|\cdot(|\mathcal{K}|-1)+\frac{|\mathcal{B}'|(|\mathcal{B}'|-1)}{2}\big) \approx \mathcal{O}\big(|\mathcal{B}|\cdot|\mathcal{K}|\big)$. Time sharing process resolves the coexistence issue between SBSs and WAPs by using KSBS. However, it requires a small amount of message passing between the coordinator and SBSs in any VC $\mathcal{V}_k$. Hence, the complexity depends on the number of SBSs $|\mathcal{B}_k|$ in $\mathcal{V}_k$ and the total complexity in this time sharing process is $\mathcal{O}(\sum_{k\in\mathcal{K}} |\mathcal{B}_k|)$. We use Q-learning algorithm for resolving the issue of resource allocation in each SBS. Using the derivation of model-free based Q-learning of [57], the complexity of Algo. 3 is $\mathcal{O}\big(\frac{N\eta^5}{\epsilon^2}\log(\frac{1}{\epsilon})(\log(N\eta)+\log\log(\frac{1}{\epsilon}))\big)$, where N is the possible number of actions and $\eta = \frac{1}{1-\vartheta}$. On the other hand, the coalition formation game algorithm of [49] has the computational complexity of $\mathcal{O}(U^4)$ with U as the total number of users and spatial adaptive play iterative algorithm of [30] has computational complexity $\mathcal{O}(\max(|\mathcal{K}|\cdot N_p, |\mathcal{U}_i|\cdot J_k)\cdot|\mathcal{B}|)$ with N_p represents the number of power levels.

VI. NUMERICAL RESULTS AND DISCUSSIONS

We verify the performance of the system based on efficiency and fairness. The system efficiency is the ratio of the total MOS of all of its users to the total number of users. To measure the system fairness, we use the proportion of unsatisfied

TABLE 2. Value of the principal simulation parameters.

$Symbol$	$Value$	$Symbol$	$Value$
B	5, 10, 15, 20, 25, 30	$\lvert\mathcal{U}_i\rvert, \forall i$	50
W	5	$\lvert\mathcal{L}_i\rvert, \forall i$	50
K	5	$J_k, \forall k$	$100 * 12$
$P_i^l, \forall i$	21 dBm	$P_i^u, \forall i$	19 dBm
σ^2	-114 dBm	a	3.4011
$\mathcal{M}$	$\{16QAM, 64QAM\}$	b	0.0984
$\mathcal{S}$	$\{WB, FD, VS(SM), VS(GW), VS(RM)\}$		
$a_1 \sim a_5$ (SM)	$2.797, -0.0065, 0.2498, 2.2073, 7.1773$		
$a_1 \sim a_5$ (GW)	$2.273, -0.0022, 0.3322, 2.4984, -3.7433$		
$a_1 \sim a_5$ (RM)	$-0.0228, -0.0065, 0.6582, 10.0437, 0.6865$		
$c_1 \sim c_4$	$0.2, 1.6, 1.5, 1$		

users as well as Jain's fairness index [58]. The metrics are defined as follows:

$$\text{Unsatisfied users} = \left[1 - \frac{\sum_{i\in\mathcal{B}}\sum_{j\in\mathcal{U}_i} \mathbb{I}(\eta_{i,j}^s \geq 3.0)}{\sum_{i\in\mathcal{B}} |\mathcal{U}_i|}\right] \times 100\%.$$

$$\text{Fairness} = \frac{\left(\sum_{i\in\mathcal{B}}\sum_{j\in\mathcal{U}_i} \eta_{i,j}^s\right)^2}{\left(\sum_{i\in\mathcal{B}} |\mathcal{U}_i|\right)\cdot\left(\sum_{i\in\mathcal{B}}\sum_{j\in\mathcal{U}_i} (\eta_{i,j}^s)^2\right)}. \tag{41}$$

SBSs and their corresponding users are distributed randomly in the considered area of radius 250 m. The WAPs operate based on the IEEE 802.11n protocol over the 5 GHz band using the request to send/clear to send (RTS/CTS) mechanism. We assume that 5 WAPs are working in 5 different 20 MHz unlicensed channels, and each SBS can also use one of these 5 unlicensed channels. The simulation parameters for the SBSs are shown in Table 2 and the Wi-Fi parameters are chosen similarly to those in [41]. We use coefficient values for a and b similar to that of [38], $a_1, \ldots, a_5$ similar to [39], and $c_1, \ldots, c_4$ similar to [40]. We compare the performance of the proposed LTE-U scheme with LTE-A, LTE-U with no cooperation among SBSs (denoted as LTE-U (NC)), LTE-U with randomly chosen users (denoted as LTE-U (Rnd)), LTE-U with Hungarian matching [59] (denoted as LTE-U (HM)), and LTE-U with NBS [15] (denoted as LTE-U (NBS)) after taking 1000 runs for all the methods.

Figures 5 and 6 respectively show the overall average MOS value, and the empirical cumulative distribution function (ECDF) of the average MOS value for different runs with a varying number of SBSs. Figure 5 shows that the average MOS resulting from the proposed method is higher than those of the other methods for all considered numbers of SBSs. The same figure also shows that the values are decreasing with increasing number of SBSs because more SBSs need to share the same unlicensed band. Especially, the MOS value of the proposed method is 18.14%, 12.75%, 7.07%, 12.09%, and 4.04% larger than those of LTE-A, LTE-U (NC), LTE-U (Rnd), LTE-U (HM), and LTE-U (NBS), respectively, for 5 SBSs, whereas this values are 5.39%, 2.77%, 2.57%, 2.43%, and 0.75% higher than those of the corresponding methods, respectively, for 30 SBSs. Figure 6 shows

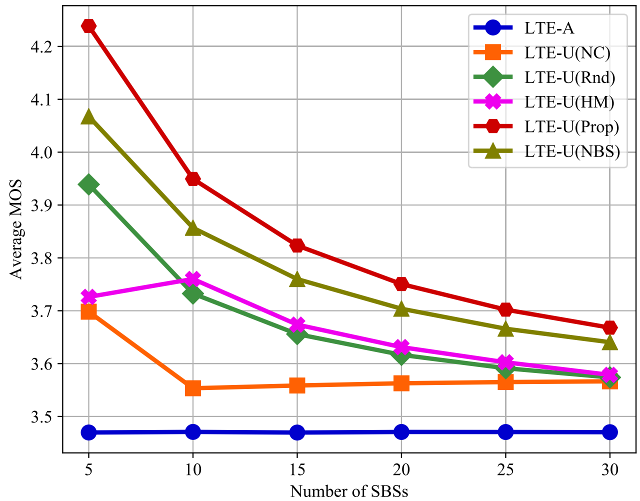

FIGURE 5. Comparison of the average MOS value with varying number of SBSs.

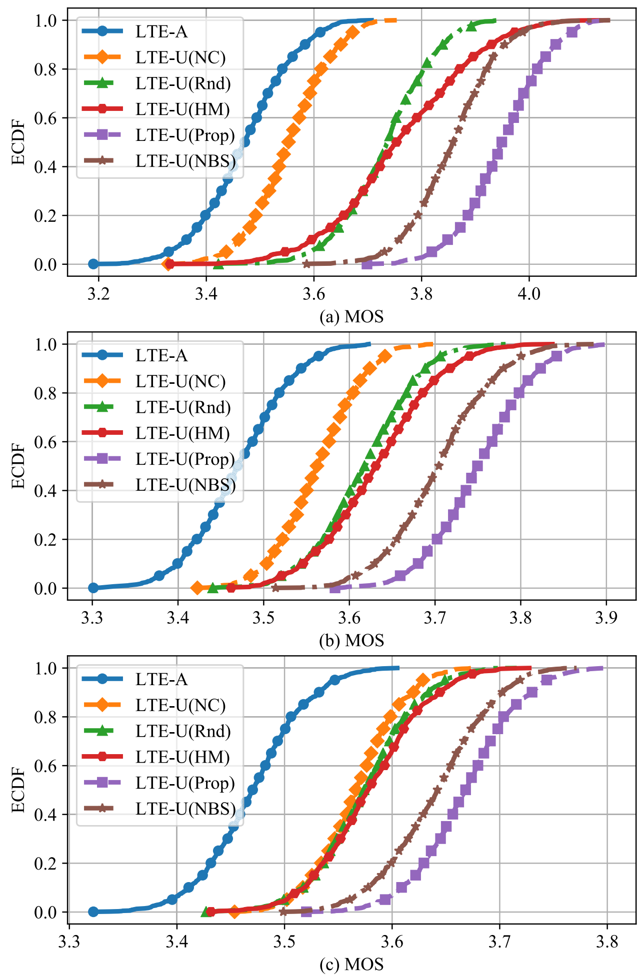

FIGURE 6. Comparison of the average MOS value for (a) 10 SBSs case, (b) 20 SBSs case, and (c) 30 SBSs case.

that the ECDF of the average MOS value resulting from the proposed method is superior to those of the other baseline methods for all the considered cases. Figure 6(a) shows that LTE-U (Prop), LTE-U (NBS), LTE-U (HM), and LTE-U (Rnd) give average MOS values of at least 3.80 with probability 0.98, 0.80, 0.40, and 0.20, respectively, while LTE-U (NC), and LTE-A can provide less than 3.80 for sure. Figure 6 (b) shows that LTE-U (Prop), LTE-U (NBS), LTE-U (HM), and LTE-U (Rnd) give average MOS values of at least 3.70 with probability 0.80, 0.55, 0.15, and 0.10, respectively, while LTE-U (NC) and LTE-A can provide less than 3.70. Figure 6 (c) shows that LTE-U (Prop), LTE-U (NBS), LTE-U (HM), LTE-U (Rnd), and LTE-U (NC) give average MOS values of at least 3.60 with probability 0.90, 0.80, 0.35, 0.25, and 0.20 respectively, while LTE-A can provides less than 3.60 for almost all times. Figure 6 also indicates that the average MOS value decreases for LTE-U (NC), LTE-U (Rnd), LTE-U (HM), LTE-U (NBS), and LTE-U (Prop) with an increasing number of SBSs, as each SBS needs to share the same unlicensed band with other SBSs, and thus the number of sub-carriers decreases for each SBS. Meanwhile it affects nothing to LTE-A as it only uses the same licensed resources. Moreover, the MOS values for LTE-U (NC) and LTE-A are almost the same for Figures 6(b) and 6(c), as the amount of interference from the other SBSs is high enough to negate the benefit of utilizing unlicensed bands.

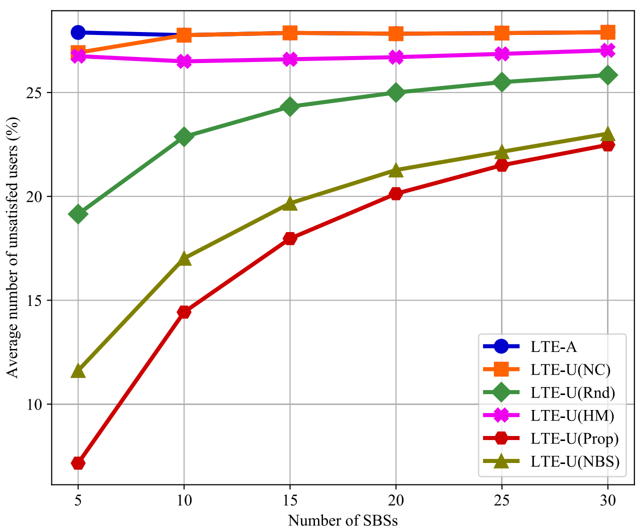

FIGURE 7. Comparison of the average number of unsatisfied users with varying number of SBSs.

In Figure 7, we present a comparison of the average number of unsatisfied users for different methods with increasing number of SBSs. Figure 7 shows that the average number of unsatisfied users resulting from the proposed method outperforms that of all other methods for all cases. We also reveal from the Figure 7 that the number of unsatisfied users increases with an increasing number of SBSs, as more SBSs need to share the same unlicensed band.

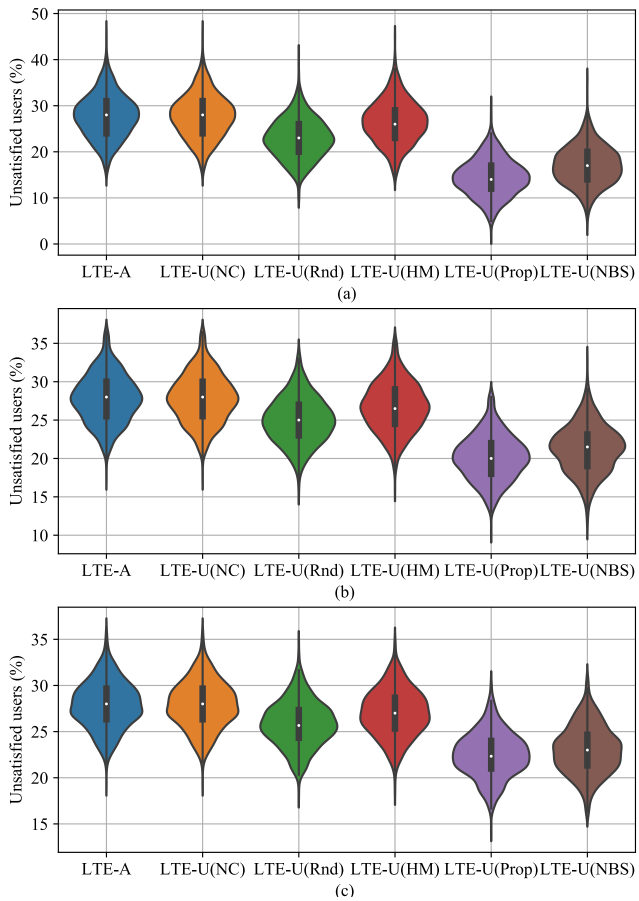

FIGURE 8. Comparison of the number of unsatisfied users for (a) 10 SBSs, (b) 20 SBSs, and (c) 30 SBSs.

In particular, the proposed method has 74.33%, 73.40%, 62.61%, 73.23%, and 38.38% less unsatisfied users than those of LTE-A, LTE-U (NC), LTE-U (Rnd), LTE-U (HM), and LTE-U (NBS), respectively, for 5 SBSs, whereas these baseline methods show 19.43%, 19.43%, 13.00%, 16.83%, and 2.35% lower performance than the proposed method for 30 SBSs, respectively. Figure 8 shows the distribution of unsatisfied users among different methods for three cases. We find from Figures 8(a), 8(b), and 8(c) that the proposed method provides better results than those of LTE-A, LTE-U (NC), LTE-U (Rnd), LTE-U (HM), and LTE-U (NBS). The number of unsatisfied users remains the same in all the three cases for LTE-A, as they use only the fixed licensed spectrum. However, the numbers increase with an increasing number of SBSs for the other four methods due to the smaller availability of unlicensed resources for each SBS. Moreover, the differences between the proposed method and the other methods decrease with an increasing number of SBSs because of the smaller amount of available unlicensed resources for the users.

In Figure 9, we compare the average fairness scores among the different methods with a varying number of SBSs. Figure 9 shows that the scores resulting from the proposed

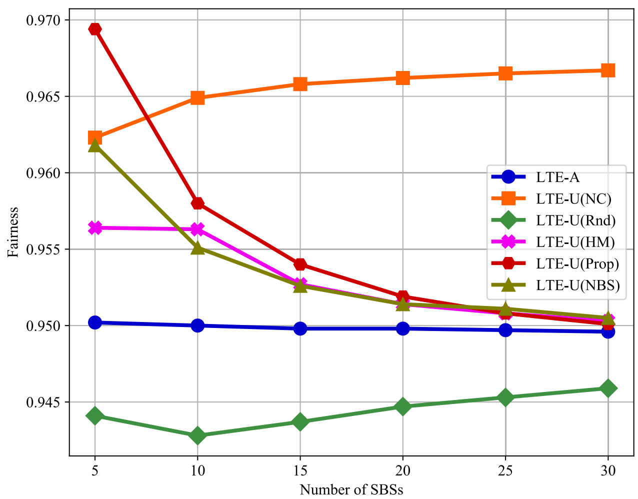

FIGURE 9. Comparison of the average fairness score with varying number of SBSs.

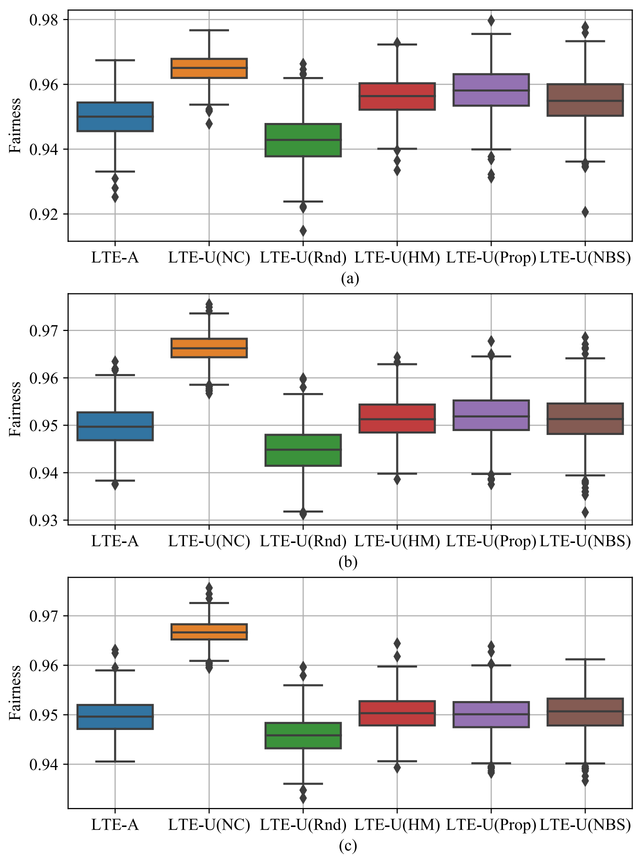

FIGURE 10. Comparison of the fairness scores for (a) 10 SBSs, (b) 20 SBSs, and (c) 30 SBSs.

method are very close to the highest scores in all scenarios. Specifically, the proposed method is 1.98%, 0.73%, 2.61%, 1.34%, and 0.78% fairer than LTE-A, LTE-U (NC), LTE-U (Rnd), LTE-U (HM), and LTE-U (NBS), respectively, for 5 SBSs, whereas the proposed method is 1.71% less fairer than LTE-U (NC) for 30 SBSs. Figure 10 shows the distribution of fairness scores among the different methods for three cases. We find from Figures 10(a), 10(b), and 10(c) that the proposed method offers a fair allocation near the highest for resources among the users. We also see from the Figure 10 that the fairness scores decrease for all methods (except LTE-A) with an increasing number of SBSs, as each SBS receives fewer unlicensed resources to satisfy the smaller number of users.

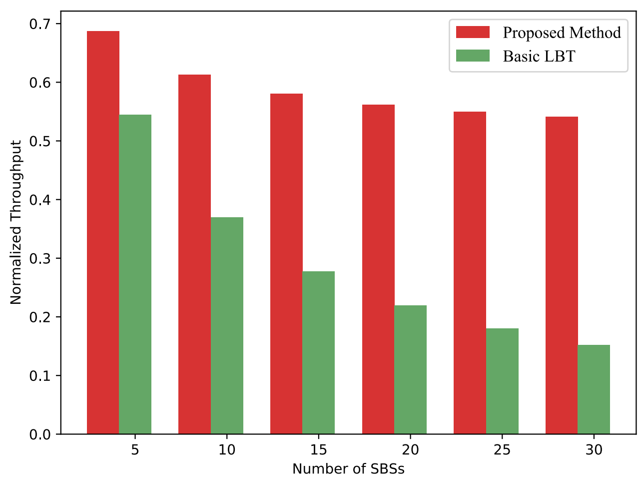

FIGURE 11. Comparison of the normalized throughput of the WAP with a varying number of SBSs.

In Figure 11, we compare the normalized throughput of the WAP between the proposed method and LBT, considering 5 $\sim$ 30 SBSs in the considered conflicting area. Figure 11 shows that the proposed method protects WAPs far better than the basic LBT mechanism in all cases. Both the proposed method and LBT provide a lower outcome for the Wi-Fi system with an increasing number SBSs, as more SBSs need to share the same channel with WAPs; however, the proposed method ensures a stable outcome for the Wi-Fi system. Moreover, the proposed method achieves 20.76%, and 71.89% higher normalized throughput for each WAP than the LBT mechanism for 5 and 30 SBSs, respectively. Thus, the proposed method protects WAPs more efficiently in dense deployment environments.

VII. CONCLUSIONS

In this paper, we have proposed a novel method that allows LTE-U and Wi-Fi networks to coexist in the same unlicensed spectrum for 5G. We formulated the problem as maximizing the QoE of the LTE-U system and solved it using a game-theoretic approach. We have solved the unlicensed band selection problem of the SBSs using a coalition game. Then, we have resolved the coexistence issue in each coalition using KSBG, whereas the resource allocation problem of each SBS is solved via a learning game (Q-learning). Simulation results show that the proposed approach provides a better average MOS value and fewer unsatisfied users than the LTE-A, LTE-U (NC), LTE-U (Rnd), LTE-U (HM), and LTE-U (NBS) methods. The proposed method also provides good fairness score compared with the other methods. Moreover, the proposed approach is better for managing Wi-Fi systems compared to basic LBT.

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