

Traffic Offloading from Licensed Band to Unlicensed Band

1 Development of Traffic Offloading

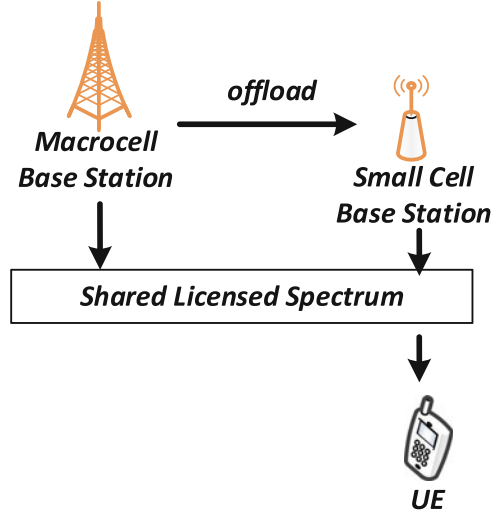
In view of the increasing requirements of mobile data rate and data applications, it becomes challenging for the traditional wireless network to meet the demands of all user equipments (UEs). Accordingly, it is beneficial and necessary to offload wireless traffic to other vacant resources. Generally, the traffic offloading is currently considered in the perspective of network architecture and wireless resource. In this section, we briefly introduce the traffic offloading in wireless communication and highlight the promising trends for traffic offloading from licensed spectrum to unlicensed spectrum with U-LTE.

1.1 Traffic Offloading in Heterogeneous Networks

The decoupling of the increasing density and variety of data services and the limited amount of wireless resource motivate the improvement of spectrum efficiency in wireless communication. Heterogeneous network, where multi-tier small cells overlaid on the traditional macrocells, becomes an effective solution.

In the heterogeneous network as shown in Fig. 1, the data traffic from the macrocell base station can be offloaded to the small cell base stations close to the UEs. Due to the small distance or indoor data transmission between small cell base station and UEs, low power transmission while high quality of service can be achieved, where the same spectrum can be reused multiple times between different small cell base station and UE pairs with tolerable interferences in the same macrocell. Thus, the general network efficiency is improved, leading to high quality of service (QoS) of all UEs.

Fig. 1 Traffic offloading in heterogeneous network



1.2 Traffic Offloading to Wi-Fi Networks

However, even though increasing high spectrum efficiency is able to relieve the traffic congestion, with the demands of data traffic exponentially increasing, wireless operators also seek for more wireless spectrum resource to meet the requirement of all UEs. On the other hand, with the fast development of Wi-Fi technology, from 802.11 to 802.11 ac, 802.11 ad and 802.11 ax, the data transmission rate nowadays has reached up to 6.7 Gbit/s. Therefore, as shown in Fig. 2, it is promising to offload the congested data traffic in wireless communication network to the Wi-Fi networks, where the unlicensed spectrum of 2.4, 5 and 60 GHz bands in Wi-Fi is able to relieve the congested traffic in wireless communication network. According to the Cisco Visual Networking Index, in 2016, 60% of total mobile data traffic was offloaded through Wi-Fi or femtocell [1]. Companies like AT&T has established and operate more than 30,000 public Wi-Fi hotspots for their wireless service offloading.

1.3 Traffic Offloading to Unlicensed Spectrum with U-LTE

Nevertheless, compared with Wi-Fi, the LTE technology is able to achieve higher performance for UEs. Accordingly, it is beneficial if LTE can be applied in unlicensed spectrum and the congested data traffic is able to be offloaded to the U-LTE, as shown in Fig. 3. However, as various other data services, e.g., Wi-Fi, are also presented in the unlicensed spectrum. In order to improve the Quality of Service (QoS) of its own user while guaranteeing the performance of other unlicensed users at the same time, it remains challenging for each operator to employ spectrum

Fig. 2 Traffic offloading to Wi-Fi Networks

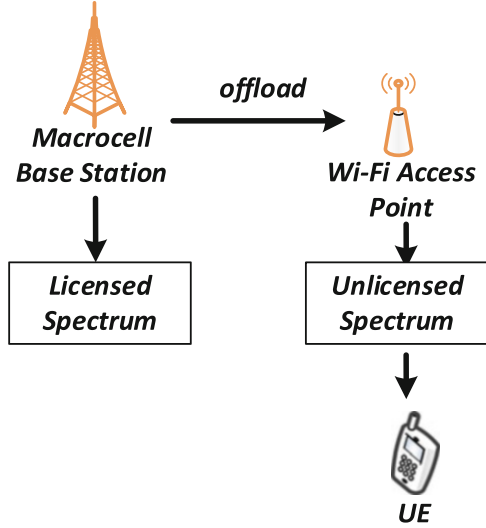
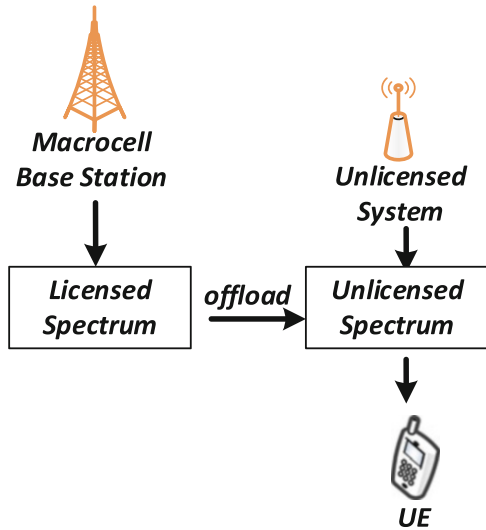


Fig. 3 Traffic offloading to unlicensed spectrum with U-LTE



allocation between licensed spectrum and unlicensed spectrum. Moreover, when multiple operators offload their service on the unlicensed spectrum simultaneously, further power control and sub-band allocation strategies are required to avoid strong interference.

From the operators' perspective, how to manage the resource allocation in both licensed and unlicensed spectrum is a critical challenge. To minimize the interference caused by the UEs in U-LTE, a dynamic traffic balancing algorithm over licensed and unlicensed spectrum was proposed for Integrated Femto-WiFi and Dual-Band Femtocell in [2]. It is shown that the algorithm can improve the overall

user experience in both licensed and unlicensed bands. In [3], a flexible resource allocation scheme is proposed to improve the efficiency of resource utilization in both licensed and unlicensed bands. By adjusting the resource on licensed and unlicensed bands dynamically based on the utility functions, the network performance can be optimized to attain the maximum utility. In [4], the authors jointly consider the power control and spectrum allocation in both licensed and unlicensed bands. With the help of convex optimization methods, the spectrum efficiency is maximized in the system. In [5], the authors propose the channel selection strategies for U-LTE enabled cells. By adopting the distributed Q-learning mechanism for channel selection, all LTE operators are able to coexist in an efficient way. In [6], a student-project allocation matching is applied to approach a stable matching results of channel allocation problem in the unlicensed spectrum.

Furthermore, continuing the system model in last chapter, the multi-operator scenarios should be considered in offload problems, where each operator tries to offload their data service from its unique but congested licensed spectrum to unlicensed spectrum. Accordingly, the resource management for each operator between licensed spectrum and unlicensed spectrum and the resource sharing for all operators in unlicensed spectrum are supposed to be jointly considered. In the unlicensed spectrum, we set the spectrum sharing scenarios in which multiple cellular operators serve a set of UEs and charge penalty prices to all UEs accessing the unlicensed spectrum according to their interference to the Wi-Fi networks. We focus on the pricing mechanism that can be applied by the cellular operators to manage and control the interference caused by each UE to other UEs as well as Wi-Fi users in the unlicensed spectrum. The amount of licensed spectrum and unlicensed spectrum allocated to each UE as well as the optimal transmit power for each UE in the unlicensed spectrum can be determined under the pricing mechanism of the operators. In this chapter, we formulate a multi-leader multi-follower Stackelberg game to study the interactions between the cellular operators and UEs. In this game, all operators first set their interference penalty price on each sub-band of the unlicensed spectrum. Based on the prices set by operators, each UE then decides its sub-bands in the unlicensed spectrum by a matching algorithm. Moreover, each UE can also optimize its transmit power to further improve its capacity without causing intolerable interference to other UEs and Wi-Fi users. Accordingly, the operators can predict the actions of the UEs and set the optimal prices to receive high utilities. We propose both non-cooperative and cooperative schemes for operators to deal with the interference problem in the unlicensed spectrum. In the non-cooperative scheme, each operator sets its prices individually without coordinating with others, and a sub-gradient algorithm is adopted to achieve the highest utility for each operator based on the behaviors of others. In the cooperative scheme, all operators are able to coordinate when they set prices. We optimize the relations of the prices with a linear programming method so as to reach the highest utilities of all operators. To the best of our knowledge, this is the first work that applies the Stackelberg game with multiple leaders and multiple followers to study the U-LTE networks. Simulation results show that the operators in both the non-cooperative and cooperative schemes can improve their utilities without causing intolerable interferences to the unlicensed users, based on different traffic conditions in the unlicensed spectrum.

The rest of this chapter is organized as follows. We introduce the system model in Sect. 2, and then formulate the problems in Sect. 3. Based on the formulated problem, we model the scenario in a multi-leader multi-follower Stackelberg game and further analyze the game in Sects. 4 and 5. We present our simulation results in Sect. 6 and finally summarize this chapter in Sect. 7.

2 System Model

We consider a heterogenous cellular network system where M co-located operators serve N UEs in an indoor environment. We assume operator i , $\forall i \in \mathcal{M} = \{1, 2, \dots, M\}$, deploys P_i Small Cell Base Stations (SCBSs) that are co-located with Q_i Wi-Fi Access Points (WAPs), randomly distributed in the coverage area. The SCBSs can serve the UEs in both the licensed and unlicensed spectrum. In the licensed spectrum, we assume all UEs operate in the same manner as the traditional LTE networks and are able to obtain licensed resource that can support C_j^l data transmission rate, $\forall j \in \mathcal{N} = \{1, 2, \dots, N\}$. If UE j is satisfied with a data transmission rate that is less than or equal to C_j^l , it will only access the licensed spectrum. If UE j requires a data transmission rate that is higher than C_j^l , UE j will then also seek spectrum resource in the unlicensed spectrum to further improve its Quality-of-Service (QoS). To simplify our description, we assume the channel gains between cellular base station and UEs can be regarded as constants, and therefore C_j^l can be regarded as a fixed value so that we can focus on the resource allocation in the unlicensed spectrum. In each sub-band of both licensed and unlicensed spectrum, we suppose there is an upper bound on the transmit power. As the resource management mechanisms in the licensed spectrum are currently mature and well-deployed in the telecommunication network, in order to adopt U-LTE without affecting the original resource management, we follow the current power control mechanism in the licensed spectrum first. If the UEs are not satisfied with the services in licensed spectrum, following the power constraint in each sub-band, the power control in the unlicensed spectrum is executed. Suppose N UEs require to access to the unlicensed spectrum. In the unlicensed spectrum, all operators utilize a common spectrum pool with Wi-Fi access points and other unlicensed users. In order to guarantee the performance of other unlicensed users, the transmit power of each UE cannot strongly interfere with other unlicensed users in the same sub-band, or surpass the available residue power. Furthermore, we assume that the UEs served by the SCBSs can be allocated with unlicensed spectrum, and that each UE chooses the operator with the SCBS closest to it. We suppose there are S sub-bands in the unlicensed spectrum. When multiple UEs are allocated with the same sub-band in the unlicensed spectrum, the UEs may cause severe interference among each other. Accordingly, we follow the same setting as our previous works [7] and consider the dynamic spectrum access systems with multiple operators. We assume all the operators can share the unlicensed spectrum with Wi-Fi networks. Each operator

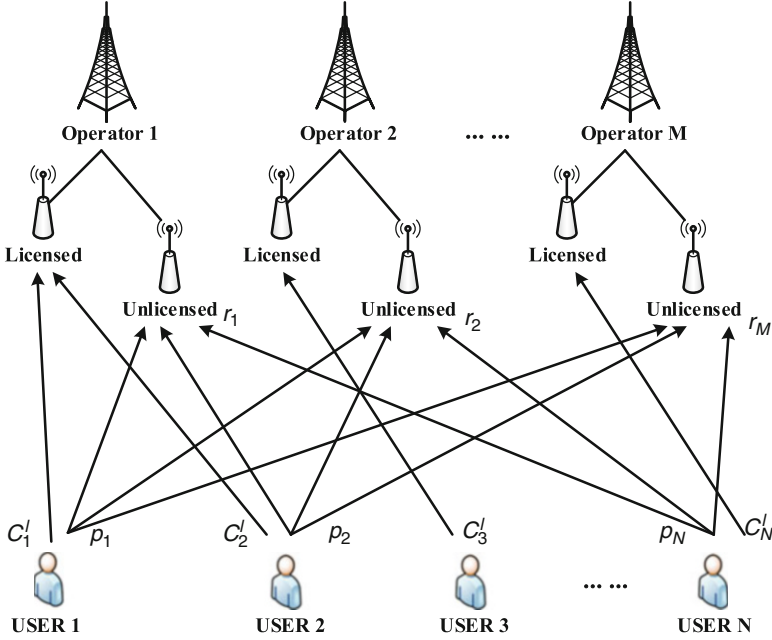


Fig. 4 System architecture in multi-operator multi-user scenario

can access any sub-band that is occupied or unoccupied by Wi-Fi users in the spectrum pool. However, each sub-band can only be accessed by one operator at each time. For the UEs served by the same operator in U-LTE, the LTE standard is applied in the unlicensed spectrum. Thus, Orthogonal Frequency Division Multiple Access (OFDMA) is adopted to avoid cross-interference. For UEs that are served by different operators, we suppose that Frequency Division Multiple Access (FDMA) is applied [8]. As shown in Fig. 4, in the unlicensed spectrum, following the settings in [9, 10, 12], before the data transmission between each UE and its serving SCBS, in the control channels, the operators are able to broadcast the prices that it would charge in the unlicensed spectrum to all the UEs because of the interference to the Wi-Fi users. Based on the prices set by all the operators, UE j , where $j \in \mathcal{N}$, determines its desired transmit power in the sub-band s , $\forall s \in \mathcal{S} = \{1, 2, \dots, S\}$, which is denoted as $p_{j,s}$.

When UE j is served by the operator i in the sub-band s , $\forall s \in \mathcal{S}$, of the unlicensed spectrum, we define the spectrum efficiency of UE j as

$$R_{j,s} = \log_2 \left(1 + \frac{p_{j,s} g_j}{Z_{j,s}} \right), \quad (1)$$

where g_j is the channel gain from the serving SCBS to UE j , $Z_{j,s}$ is the total interference measured by UE j in the sub-band s . Receiving the training data, the serving SCBS are able to feedback the estimated channel response g_j and interference $Z_{j,s}$ to UEs for decisions [13].

Accordingly, we suppose B_u is the size of each sub-band in the unlicensed spectrum. If UE j , $\forall j \in \mathcal{N}$, is served in both the licensed and unlicensed spectrum, the utility of UE j can be shown as

$$U_j = C_j^l + \sum_{s=1}^S \lambda_{j,s} \left(\gamma_j B_u R_{j,s} - \sum_{i=1}^M \sum_{k=1}^{Q_i} r_i h_{ikj} p_{j,s} \right), \quad (2)$$

where $\gamma_j B_u R_{j,s}$ is the profit that UE j receives from the services in the sub-band s , $\forall s \in \mathcal{S}$, of the unlicensed spectrum. γ_j is the revenue that UE j gains for unit data rate transmitted. r_i is the penalty price for unit watt of operator i in the unlicensed spectrum, h_{ikj} is the channel gain from the k th WAP of operator i to UE j , and $p_{j,s}$ is the transmit power of UE j in the sub-band s , $\forall s \in \mathcal{S}$, of the unlicensed spectrum. As the data transmission in the unlicensed spectrum causes interference to the WAPs nearby, we set $r_i p_{j,s} h_{ikj}$ as the interference penalty from the k th WAP of operator i to UE j in the sub-band s of the unlicensed spectrum, $k \in \mathcal{K}_i = \{1, 2, \dots, Q_i\}$, $i \in \mathcal{M}$, $\forall s \in \mathcal{S}$. The WAPs of operators can forward the information to the core communication network and feedback the estimated channel gain h_{ikj} to UEs for decisions. $\lambda_{j,s}$ is a binary number determining whether or not the sub-band s is allocated to UE j .

Accordingly, the utility of operator i is defined as the revenues received from all WAPs of the operator to all the UEs in the unlicensed spectrum, i.e., $\forall i \in \mathcal{M}$,

$$W_i = r_i \sum_{s=1}^S \sum_{j=1}^N \left(\lambda_{j,s} p_{j,s} \sum_{k=1}^{Q_i} h_{ikj} \right). \quad (3)$$

3 Problem Formulation

In a cellular network system with multiple operators and UEs, it is possible that not every operator is always interested to coordinate with others. We therefore consider two specific scenarios: all the operators can either non-cooperate with each other or can fully coordinate with each other by forming as a group. When some operators cooperate and do not cooperate, we can combine the above two situations and solve the problem.

When the operators are not fully coordinated with each other, they can make decisions in a distributed manner, i.e., operator i sets its price \mathbf{r}_i of the interference penalty to all UEs served on all sub-bands in the unlicensed spectrum. Not only should it predict the reactions of all the UEs, but it also needs to consider the behaviors of other operators in order to receive satisfying revenues. Therefore, the optimization problem for operator i is,

$$\begin{aligned} & \max_{r_i} W_i(r_i | \mathbf{r}_{-i}^*, \mathbf{p}^*), \quad \forall i \in \mathcal{M}, \\ & \text{s.t.} \begin{cases} \mathbf{r}^* \geq \mathbf{0}, \\ p_{j,s}^* \geq 0, \quad \forall j \in \mathcal{N}, \forall s \in \mathcal{S}, \\ p_{j,s}^* < p_{j,s}^{\max}, \quad \forall j \in \mathcal{N}, \forall s \in \mathcal{S}, \end{cases} \end{aligned} \quad (4)$$

where \mathbf{r}_{-i}^* is the set of the optimal pricing strategies of all other operators except operator i on all sub-bands of the unlicensed spectrum. $\mathbf{r}^* = [r_1^*, r_2^*, \dots, r_M^*]$ is the set of the optimal pricing strategies of all operators. $\mathbf{0} = [0, 0, \dots, 0]$ is the set with M elements, each of which is zero. $\mathbf{p}^* = [p_1^*, p_2^*, \dots, p_N^*]$ is the set of the optimal transmit powers of all UEs on all sub-bands of the unlicensed spectrum. In order to manage the interference to ensure the service of unlicensed users nearby, the operators should control the transmit power of each UE. We define $p_{j,s}^{\max}$ as the maximum transmit power of UE j in the sub-band s of the unlicensed spectrum, $\forall j \in \mathcal{N}, \forall s \in \mathcal{S}$.

Furthermore, when all operators are able to cooperate with each other, all operators aim to achieve the maximum total utility. Accordingly, before setting prices of interference for all UEs in the unlicensed spectrum, operators are only required to predict the transmit power of all UEs so as to achieve high utilities. The optimization problem for all operators is then formulated as follows,

$$\begin{aligned} & \max_{\mathbf{r}} \sum_{i=1}^M \alpha_i W_i(\mathbf{r}), \\ & \text{s.t.} \begin{cases} \mathbf{r} \geq \mathbf{0}, \\ p_{j,s}^* \geq 0, \quad \forall j \in \mathcal{N}, \forall s \in \mathcal{S}, \\ p_{j,s}^* < p_{j,s}^{\max}, \quad \forall j \in \mathcal{N}, \forall s \in \mathcal{S}, \end{cases} \end{aligned} \quad (5)$$

where $\alpha_i, \forall i \in \mathcal{M}$ is the weight factors for operator i . If α_i increases, operator i plays a more significant role in the cooperation.

According to the optimal prices set by all operators \mathbf{r}^* , UE j determines the transmit power strategy in each sub-band of the unlicensed spectrum $p_{j,s}$. Accordingly, the optimization problem for UE j satisfies,

$$\begin{aligned} & \max_{p_{j,s}, \lambda_j} U_j(p_{j,s} | \mathbf{r}^*, \boldsymbol{\lambda}_{-j}), \quad \forall j \in \mathcal{N}, \forall s \in \mathcal{S}, \\ & \text{s.t.} \begin{cases} p_{j,s} > 0, \\ p_{j,s} < p_{j,s}^{\max}, \\ \lambda_{j,s} B_u R_j \geq \lambda_{j,s} \sum_{i=1}^M \sum_{k=1}^{Q_i} r_i h_{ikj} p_{j,s}, \end{cases} \end{aligned} \quad (6)$$

where $\boldsymbol{\lambda}_j = [\lambda_{j,1}, \dots, \lambda_{j,S}]$ is the sub-band allocation result for UE j , $\boldsymbol{\lambda}_{-j}$ is the sub-band allocation results for all other UEs except UE j . The received revenue of UE j , i.e., $B_u R_j$, in the serving sub-band should be no less than the interference penalty the

UE pays to all operators $\sum_{i=1}^M \sum_{k=1}^{Q_i} r_i h_{ikj} p_{j,s}$. As the UEs are unable to acknowledge the information of Wi-Fi users, we let the operators to set prices to restrict the transmit power of UEs. When the price imposed by each operator is high, no UE can afford the prices and therefore no UE will access the service provided by each operator. Therefore, in the formulated problem of operators, we set the power constraint for all UEs to guarantee the basic data transmission of Wi-Fi users.

Based on the above formulations, all operators and UEs are autonomous decision makers who would like to maximize their own utilities in a selfish manner. In order to analyze the problem of resource allocations in the unlicensed spectrum, we model the scenario as a multi-leader multi-follower Stackelberg game, where all operators are leaders and all UEs are followers. In the game, each operator first sets its penalty price of interference in the unlicensed spectrum. Based on the prices set by all operators, each UE determines its optimal transmit power. In the following sections, backward induction is adopted to analyze the problems. We first discuss the strategy of each UE, given the penalty price of interference set by all operators. Then, with the prediction of the optimal behaviors of each UE, we design a sub-band allocation scheme with matching theory and propose the corresponding non-cooperative or cooperative strategies for operators to achieve the maximum utilities.

4 Analysis of UEs

Observing the prices set by operators, the UEs are supposed to adopt strategies for optimal utilities. In this section, we first analyze the optimal power transmission strategies for the UEs. Based on the optimal transmit power on each sub-bands of the unlicensed spectrum, we then design a sub-band allocation scheme with matching theory for high utilities.

4.1 Strategies of Power Transmission for UEs

In the formulated multi-leader multi-follower Stackelberg game, all UEs act as followers. In order to receive high revenues from the services and reduce the interference penalty to other operators, based on the prices set by operators i , $\forall i \in \mathcal{M}$, UE j optimizes its transmit power $p_{j,s}$ in the sub-band s of the unlicensed spectrum, $\forall j \in \mathcal{N}$, $\forall s \in \mathcal{S}$. The optimal transmit power for each UE is relative to the prices set by all operators. Lemma 1 is developed as follows.

Lemma 1 *If UE j is served by operator i in the unlicensed spectrum, $\forall i \in \mathcal{M}$, $\forall j \in \mathcal{N}$, the optimal transmit power to UE j on the sub-band is*

$$p_{j,s}^* = \left(\frac{B_u}{\sum_{i=1}^M \sum_{k=1}^{Q_i} h_{ikj} r_i} - \frac{1}{q_{j,s}} \right)^+, \quad (7)$$

where

$$(x)^+ = \max \{x, 0\}, \quad (8)$$

and

$$q_{j,s} = \frac{g_j}{Z_{j,s}}. \quad (9)$$

In (7), as the channel gain $g_{j,s}$ is related to the distance between UE j and its serving SCBS, and the channel gain h_{ikj} is related to the distance between the k th WAP of the operator i and UE j , we discover that when the distance between UE j and its serving SCBS increases, the channel gain $g_{j,s}$ decreases. Thus, the optimal transmit power $p_{j,s}$ in the sub-band s decreases. When the distances between the UE j and the k th WAP of the operator i increases, the value of channel gain h_{ikj} decreases. Thus the optimal transmit power $p_{j,s}$ in the sub-band s increases.

Proof When UE j is allocated with the unlicensed spectrum, the utility function of UE j is continuous. We take the second derivative of U_j with respect to $p_{j,s}$, i.e., $\forall s \in \mathcal{S}$,

$$\frac{\partial^2 U_j}{\partial p_{j,s}^2} = -\frac{B_u q_{j,s}^2}{(1 + p_{j,s} q_{j,s})^2}. \quad (10)$$

The second derivative of U_j with respect to $p_{j,s}$ is negative, so U_j is quasi-concave in $p_{j,s}$. Accordingly, when the first derivative of U_j with respect to $p_{j,s}$ is equal to zero, i.e., $\forall s \in \mathcal{S}$,

$$\frac{\partial U_j}{\partial p_{j,s}} = \frac{B_u q_{j,s}}{1 + p_{j,s} q_{j,s}} - \sum_{i=1}^M \sum_{k=1}^{Q_i} h_{ikj} r_i = 0, \quad (11)$$

the utility function of UE j achieves the maximum value, where the transmit power from the operator i to UE j in the sub-band s , $\forall s \in \mathcal{S}$, of the unlicensed spectrum satisfies

$$p_{j,s} = \frac{B_u}{\sum_{i=1}^M \sum_{k=1}^{Q_i} h_{ikj} r_i} - \frac{1}{q_{j,s}}. \quad (12)$$

Furthermore, the transmit power $p_{j,s}$ follows the constraint $p_{j,s} \in [0, p_{j,s}^{\max}]$. On one hand, according to the properties of quasi-concave function, if the value of (12) is negative, the optimal solution in the feasible region is $p_{j,s}^* = 0$, i.e., there are many other UEs and unlicensed users transmitting information on the sub-band s of the unlicensed spectrum. Thus, the transmit power on the sub-band is zero because of the high interference penalty. On the other hand, each UE is unaware of the interference it will cause to other unlicensed users when it accesses each sub-band. For UE j , if $p_{j,s}$ is larger than the maximum transmit power constraint $p_{j,s}^{\max}$ in the sub-band s of the unlicensed spectrum, the UE j will cause severe interference to all other unlicensed users in the sub-band. In order to ensure the performance of other unlicensed users, we suppose the transmit power for each UE in the unlicensed spectrum can be predicted and controlled by the operators, which will be illustrated in the following sections.

Correspondingly, when UE j is served in the sub-band s , $\forall s \in \mathcal{S}$, of the unlicensed spectrum, the maximum utility of UE j in the sub-band, if $p_{j,s}^* = 0$, is

$$u_{j,s} = 0, \quad (13)$$

where $u_{j,s}$ is the utility of UE j in the sub-band s of the unlicensed spectrum, $\forall j \in \mathcal{N}$, $\forall s \in \mathcal{S}$. If $p_{j,s}^* > 0$, we have

$$u_{j,s} = B_u \log_2 \left(\frac{q_{j,s}}{\sum_{i=1}^M \sum_{k=1}^{Q_i} h_{ikj} r_i} \right) - B_u + \frac{\sum_{i=1}^M \sum_{k=1}^{Q_i} h_{ikj} r_i}{q_{j,s}}, \quad (14)$$

where the optimal utility is related to the prices of operator i in the game, $\forall i \in \mathcal{M}$. In (14), we take the second derivative of $u_{j,s}$ with respect to r_i , i.e.,

$$\frac{\partial^2 u_{j,s}}{\partial r_i^2} = \frac{B_u \left(\sum_{k=1}^{Q_i} h_{ikj} \right)^2}{\left(\sum_{i=1}^M \sum_{k=1}^{Q_i} h_{ikj} r_i \right)^2}. \quad (15)$$

We discover $\frac{\partial^2 u_{j,s}}{\partial r_i^2} \leq 0$, i.e., the optimal utility of each UE is quasi-convex with respect to the penalty prices set by operator i , if the penalty prices of all other operators keep unchanged. Accordingly, we set the first derivative of $u_{j,s}$ with respect to r_i equal to zero,

$$\frac{\partial u_{j,s}}{\partial r_i} = - \frac{B_u \sum_{k=1}^{Q_i} h_{ikj}}{\sum_{i=1}^M \sum_{k=1}^{Q_i} h_{ikj} r_i} + \frac{\sum_{k=1}^{Q_i} h_{ikj}}{q_{j,s}}. \quad (16)$$

Thus,

$$\sum_{i=1}^M \sum_{k=1}^{Q_i} h_{ikj} r_i = B_u q_{j,s}. \quad (17)$$

Based on the above, when the price of operator i increases and the prices of all other operators are unchanged, the utility of UE j first decreases. When the increasing price satisfies (17), the utility of UE j stops decreasing and starts to increase as the price continuously increases.

4.2 Sub-band Allocation Scheme

During service, as each UE prefers to be allocated with the sub-band for high utility, we construct a preference list for UE j based on the utility $u_{j,s}$ in each sub-band s , such that

$$PL_{UE}(j, s) = u_{j,s}. \quad (18)$$

Considering the optimal transmit power strategies of all UEs, we take the second derivative of $u_{j,s}$ with respect to $Z_{j,s}$, i.e.,

$$\frac{\partial^2 u_{j,s}}{\partial Z_{j,s}^2} = \frac{B_u}{(Z_{j,s})^2}, \quad (19)$$

which is larger than zero, i.e., the $u_{j,s}$ is a quasi-convex function with respect to $Z_{j,s}$. Accordingly, we set the first derivative of $u_{j,s}$ with respect to $Z_{j,s}$ equal to zero, such that,

$$\frac{\partial u_{j,s}}{\partial Z_{j,s}} = -\frac{B_u}{Z_{j,s}} + \frac{\sum_{i=1}^M \sum_{k=1}^{Q_i} h_{ikj} r_i}{g_j} = 0. \quad (20)$$

Thus

$$Z_{j,s}^* = \frac{B_u g_j}{\sum_{i=1}^M \sum_{k=1}^{Q_i} h_{ikj} r_i}. \quad (21)$$

When $Z_{j,s}$ is less than $Z_{j,s}^*$, and $Z_{j,s}$ is increasing, the utility $u_{j,s}$ decreases. When $Z_{j,s}$ surpasses $Z_{j,s}^*$, the utility $u_{j,s}$ starts increasing. Moreover, according to the constraint $p_{j,s} > 0$, we have

$$Z_{j,s}^* < \frac{B_u g_j}{\sum_{i=1}^M \sum_{k=1}^{Q_i} h_{ikj} r_i}. \quad (22)$$

Therefore, with $Z_{j,s}$ increasing, the utility $u_{j,s}$ monotonously decreases in the available region. Accordingly, UE j prefers to be served in the sub-band s with low interference from other unlicensed users $Z_{j,s}$.

Moreover, we construct a preference list for sub-band s based on the total revenue the operators receive from the sub-band s , which is denoted as w_s , $\forall s \in \mathcal{S}$,

$$PL_{SB}(s, j) = w_s. \quad (23)$$

Based on the predictions of all UEs' optimal strategies, the w_s can be expressed as follows,

$$w_s = \sum_{i=1}^N \sum_{j=1}^N \sum_{k=1}^{Q_i} r_i \lambda_{j,s} h_{ikj} \left(\frac{B_u}{\sum_{l=1}^M \sum_{k=1}^{Q_l} h_{lkj} r_l} - \frac{Z_{j,s}}{g_j} \right). \quad (24)$$

We take the first derivative of w_s with respect to $Z_{j,s}$ and discover that the value of w_s is monotonously decreasing when $Z_{j,s}$ increases. Therefore, each sub-band s prefers to be allocated to the UE with small interference.

Based on the preference lists from both UEs and sub-bands, we design a resident-oriented Gale-Shapley (RGS) algorithm [14] for sub-band allocation, which is shown in Algorithm 1. In Algorithm 1, each UE first proposes to its desired sub-bands based on its preference list. According to the proposal from all UEs, if more than one UE chooses the same sub-band, the sub-band keeps the most preferred UE based on its preference list and reject all the rest. The rejected UEs then continue to propose to its preferred sub-bands based on the rest of its preference list. The circulation continues until each UE is either allocated with sub-bands in the unlicensed spectrum, or rejected by all the sub-bands on their preference lists. The UE which is rejected by all the sub-bands on their preference lists will be only allocated with licensed spectrum for services.

Lemma 2 *Following Algorithm 1, the RGS algorithm will ultimately converge and achieve a stable matching result.*

Proof The detailed proof can be found in [14, 15].

5 Analysis of Operators

Based on the predictions of the UEs' behaviors and the sub-band allocation results, we first consider that all operators are non-cooperative with each other. Each operator is required to consider the behaviors of other operators and determine its optimal strategy. Afterwards, we propose a cooperative scheme where all operators make decisions in a coordinated way so as to achieve high utility of all operators.

Algorithm 1 RGS algorithm for sub-band allocation

```

1: for UE  $j$  do
2:   Construct the preference list of sub-bands  $PL_{UE}$  based on the value of  $Z_{j,s}$ ;
3: end for
4: for Sub-band  $s$  do
5:   Construct the preference list of UEs  $PL_{SB}$  based on the value of  $Z_{j,s}$ ;
6: end for
7: while the system is unmatched do
8:   UEs propose to sub-bands;
9:   for Unmatched UE  $j$  do
10:    Propose to first sub-band  $c_j$  in its preference list;
11:    Remove  $c_j$  from the preference list;
12:   end for
13:   Sub-bands make decisions;
14:   for Sub-band  $s$  do
15:    if 1 or more than 1 UE propose to the sub-band then
16:      The sub-band  $s$  chooses the most preferred UE and rejects the rest;
17:    end if
18:   end for
19: end while

```

5.1 Noncooperative Strategies for Operators

In the unlicensed spectrum, based on the predictions of all UEs' optimal strategies, the utility function of operator i , $\forall i \in \mathcal{M}$, satisfies

$$W_i = \sum_{s=1}^S \sum_{j=1}^N \sum_{k=1}^{Q_i} \lambda_{j,s} r_i h_{ikj} \left(\frac{B_u}{\sum_{l=1}^M \sum_{k=1}^{Q_i} h_{lkj} r_l} - \frac{1}{q_{j,s}} \right). \quad (25)$$

Accordingly, each operator is required to determine its prices on the unlicensed spectrum for satisfactory utilities. We take the second derivative of operator i 's utility function,

$$\frac{\partial^2 W_i}{\partial r_i^2} = - \sum_{s=1}^S \sum_{j=1}^N \sum_{k=1}^{Q_i} 2\lambda_{j,s} b_j h_{ikj} A_j < 0. \quad (26)$$

where

$$A_j = \frac{B_u \sum_{k=1}^{Q_i} h_{ikj} \sum_{l=1, l \neq i}^M \sum_{k=1}^{Q_i} h_{lkj} r_l}{\left(\sum_{l=1}^M \sum_{k=1}^{Q_i} h_{lkj} r_l \right)^3}. \quad (27)$$

As the second derivative of W_i with respect to r_i is negative, W_i is a concave function.

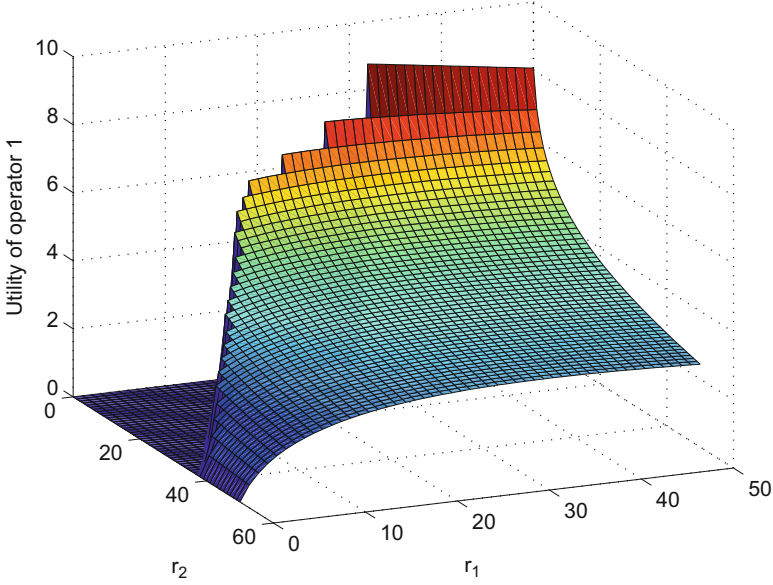


Fig. 5 The utility of operator 1 vs. the prices set by all operators

To better analyze the problem, without loss of generality, assume there are two operators and two UEs in the unlicensed spectrum. With different prices set by both operators, the utilities of both operators are shown in Figs. 5 and 6, respectively.

In both figures, the x axis denotes the price set by operator 1, and the y axis is the price set by operator 2. In Fig. 5, z axis refers to the utility of operator 1. In Fig. 6, z axis refers to the utility of operator 2. We observe that when the prices of one operator is fixed, the utility of the other operator is a concave function of its price.

Moreover, the transmit power is constrained with $p_{j,s} \in [0, p_{j,s}^{\max}]$, $\forall j \in \mathcal{N}$, $\forall s \in \mathcal{S}$. Thus, on one hand, if the prices are set too high, no UE can afford the high payment. The optimal transmit power of each UE calculated from (7) is $p_{j,s} = 0$. In this case, operators cannot get any revenue. On the other hand, if the prices are set too low, in order to avoid interference with Wi-Fi users, the highest transmit power cannot surpass $p_{j,s}^{\max}$, resulting in low revenue for each operator. Accordingly, the price of each operator has upper and lower bounds, satisfying,

$$p_{j,s} = \frac{B_u}{\sum_{i=1}^M \sum_{k=1}^{Q_i} h_{ikj} r_i} - \frac{1}{q_{j,s}} \in [0, p_{j,s}^{\max}], \quad \forall j \in \mathcal{N}, \quad \forall s \in \mathcal{S}. \quad (28)$$

Hence, we consider a linear combination of prices set by all operators as

$$R = \sum_{i=1}^M \sum_{k=1}^{Q_i} h_{ikj} r_i. \quad (29)$$

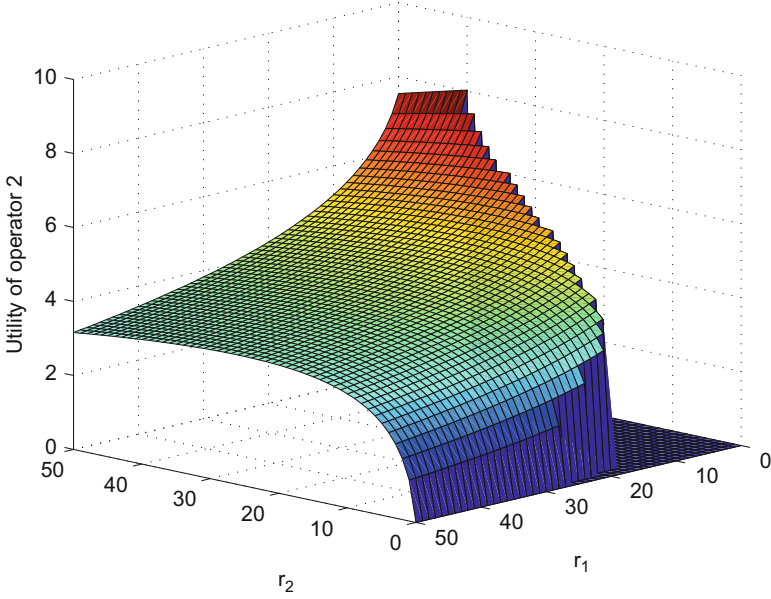


Fig. 6 The utility of operator 2 vs. the prices set by all operators

Based on the constraints of all UEs' transmit power, for operator i , $\forall i \in \mathcal{M}$, the prediction of prices set by all other operators in the sub-band s of the unlicensed spectrum follows the constraint,

$$R \in \left[\frac{B_u q_{j,s}}{p_{j,s}^{\max} q_{j,s} + 1}, B_u q_{j,s} \right]. \quad (30)$$

Therefore, in order to achieve a Nash Equilibrium solution of the problem, based on the sub-band allocation results, we adopt the sub-gradient method for the pricing strategies of operators. The method is shown in Algorithm 2. In Algorithm 2, all operators start with a high price, such that no UEs would like to be served in the unlicensed spectrum. Then in each round of the circulation, for operator i , $\forall i \in \mathcal{M}$, we set a small step Δ and changes its current prices r_i with Δ higher or lower than the original price. If the utility is the highest when the price increases with Δ , in the next round, the price changes to be $r_i + \Delta$. If the utility is the highest when the price decreases with Δ , in the next round, the price changes to be $r_i - \Delta$. Otherwise, the price remains unchanged. the circulation continues until all operators can not deviate from their current price unilaterally for higher utilities.

Lemma 3 *When the starting price and the original step size Δ are fixed, the game can always converge to a unique outcome, which is also the Nash equilibrium of the game.*

Algorithm 2 Strategy of operators in U-LTE

```

1: Initially, each operator sets high price. Thus, the transmits power of all UEs equal 0.
2: while At least one operator adjusts its price do
3:   for UE  $j$  do
4:     Based on the price set by all operators and the sub-band allocation results, each UE
       determines the optimal transmit power in unlicensed spectrum.
5:   end for
6:   for operator  $i$  do
7:     Each operator stores the current value of the service prices,  $\mathbf{r}_{old} = \mathbf{r}$ .
8:     Each operator tries to increase and decrease its price with a small step  $\Delta = \Delta \times 0.99$ ,
       and calculates its own payoff based on the prediction of the followers' optimal strategies.
9:     if  $R(\mathbf{r}_{old} - \Delta) < \frac{B_u q_i}{P_j^{\max} q_i + 1}$  then
10:      The Wi-Fi users is interfered.  $W_i = -\text{inf}$ .
11:    end if
12:    if  $W_i(r_{old_i}, \mathbf{r}_{old_{-i}}) \leq W_i(r_{old_i} + \Delta, \mathbf{r}_{old_{-i}})$  and  $W_i(r_{old_i} - \Delta, \mathbf{r}_{old_{-i}}) \leq W_i(r_{old_i} + \Delta, \mathbf{r}_{old_{-i}})$ 
       then
13:       $r_i = \min\{r_i^{\max}, r_{old_i} + \Delta\}$ ; % Increase the price
14:    else
15:      if  $U_i(r_{old_i}, \mathbf{r}_{old_{-i}}) \leq U_i(r_{old_i} - \Delta, \mathbf{r}_{old_{-i}})$  and  $W_i(r_{old_i} + \Delta, \mathbf{r}_{old_{-i}}) \leq W_i(r_{old_i} - \Delta, \mathbf{r}_{old_{-i}})$ 
       then
16:         $r_i = \max\{0, r_{old_i} - \Delta\}$ ; % Reduce the price
17:      else
18:         $r_i = r_{old_i}$ ; % Keep the price unchanged
19:      end if
20:    end if
21:  end for
22: end while

```

Proof The convergence of the sub-gradient algorithm has been proved in [16] and [17]. According to [16] and [17], the sub-gradient algorithm is able to achieve an optimal solution with small ranges in convex optimization. Therefore, with given moving step size, each operator is unable to unilaterally adjust its price in order to receive higher utility when the sub-gradient algorithm converges to an optimal solution.

Furthermore, when the starting price and the original Δ are fixed, the results in the second iteration are fixed. According to the mathematical induction, we suppose that at the Q th iteration, the prices of operators are fixed. Then in the $(Q + 1)$ th iteration, in accordance with the proposed sub-gradient strategy, the step size is fixed, and the direction from the current iteration to the next iteration is unique. Therefore, the prices of operators in the $(Q + 1)$ th iteration are also fixed. Based on the above, the game can converge to a unique outcome, when the starting price and the original Δ are fixed.

5.2 Cooperative Strategies for Operators

Nevertheless, in order to make full use of wireless resources and achieve high revenues, some wireless operators may cooperate with each other in the unlicensed spectrum. In this subsection, we analyze the behaviors of operators when they cooperate and optimize the weighted utilities of all operators, such that,

$$W^{all} = \sum_{i=1}^M \alpha_i W_i. \quad (31)$$

According to the strategies of all UEs, when all operators set different prices for interference, the transmit power of UEs may be different. However, in order to avoid the interference to nearby unlicensed users, the transmit power of each UE i th is constrained as $p_{j,s} \in [0, p_j^{\max}]$. Therefore, if the transmit power of all UEs is maintained in a feasible region, the prices of all operators $\mathbf{r} = [r_1, r_2, \dots, r_M]$ should satisfy

$$\sum_{i=1}^M \sum_{k=1}^{Q_i} h_{ikj} r_i \leq B_u q_{j,s}, \quad \forall j \in \mathcal{N}, \forall s \in \mathcal{S}, \quad (32)$$

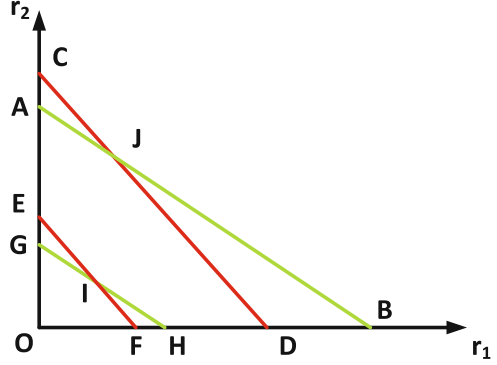
$$\sum_{i=1}^M \sum_{k=1}^{Q_i} h_{ikj} r_i \geq \frac{B_u q_{j,s}}{p_{j,s}^{\max} q_{j,s} + 1}, \quad \forall j \in \mathcal{N}, \forall s \in \mathcal{S}. \quad (33)$$

Take an example of two operators in the game. We suppose there are two sub-bands in the unlicensed spectrum, which are allocated to two UEs. Following the modeling in [11], we denote the relations of pricing between operator 1 and operator 2 in Fig. 7. The x axis shows the prices set by operator 1, r_1 , and the y axis shows the price set by operator 2, r_2 . Correspondingly, according to (32), the upper bound of prices for UEs 1 and 2 are line segments AB and CD, respectively. The lower bound of prices for UEs 1 and 2 are line segments EF and GH, respectively. When both operators set prices higher than the upper bound, the UE cannot afford the interference penalty and the transmit power is zero. Therefore, in the region above CJ and JB, there are no UE served in the unlicensed spectrum. In the region BDI, only UE 1 is served in the unlicensed spectrum. In the region ACJ, only UE 2 is served in the unlicensed spectrum. In the region AJDHI, both UEs are served in the unlicensed spectrum. Furthermore, in order to avoid interference to Wi-Fi users in the unlicensed spectrum, the transmit power of all users should satisfy

$$\sum_{i=1}^M \sum_{k=1}^{Q_i} h_{ikj} r_i \geq \max \left\{ \frac{B_u q_{j,s}}{p_{j,s}^{\max} q_{j,s} + 1}, \forall j \in \mathcal{N}, \forall s \in \mathcal{S} \right\}, \quad (34)$$

namely, in the example, the feasible region of the prices should be above EI and IH.

Fig. 7 The feasible region of the game



As all operators cooperate with each other, we assume that the prices set by all operators satisfy

$$r_i = \theta_i r_1, \quad \forall i \in \{2, 3, \dots, M\}. \quad (35)$$

Substituting (35) into (25), we have

$$W_i = \sum_{s=1}^S \lambda_{j,s} \left(\theta_i \sum_{j=1}^N \frac{B_u \sum_{k=1}^{Q_i} h_{ikj}}{\sum_{l=1}^M \sum_{k=1}^{Q_i} h_{lkj} \theta_l} - r_i K_{i,s} \right), \quad (36)$$

where

$$K_{i,s} = \sum_{j=1}^N \frac{\sum_{k=1}^{Q_i} h_{ikj}}{q_{j,s}}. \quad (37)$$

Accordingly, the total utility of operators can be derived as

$$W^{all} = \sum_{i=1}^M \alpha_i \sum_{s=1}^S \lambda_{j,s} \left(\theta_i \sum_{j=1}^N \frac{B_u \sum_{k=1}^{Q_i} h_{ikj}}{\sum_{l=1}^M \sum_{k=1}^{Q_i} h_{lkj} \theta_l} - K_{i,s} r_i \right). \quad (38)$$

It is observed that when the relations of prices are fixed, the first part of W^{all} in (38) is not related to the value of prices. Based on the expression in the second part of W^{all} , W^{all} is linearly decreasing with each $r_i, \forall i \in \mathcal{M}$. Therefore, we have the following lemma.

Lemma 4 *The optimal solution to achieve the maximum W^{all} lies in the boundary*

$$\sum_{i=1}^M \sum_{k=1}^{Q_i} h_{ikj} r_i \geq \max \left\{ \frac{B_u q_{j,s}}{p_{j,s}^{\max} q_{j,s} + 1}, \forall j \in \mathcal{N}, \forall s \in \mathcal{S} \right\}. \quad (39)$$

The position of the solution in the boundary depends on the parameters $K_{i,s}$, $\forall i \in \mathcal{M}$, $\forall s \in \mathcal{S}$ of prices.

Proof When the UEs receive services in the unlicensed spectrum, in order to guarantee the performance of Wi-Fi users, the transmit power cannot be above the upper bound. Correspondingly, the price set by operators cannot be lower than the boundary

$$\sum_{i=1}^M \sum_{k=1}^{Q_i} h_{ikj} r_i \geq \max \left\{ \frac{B_u q_{j,s}}{p_{j,s}^{\max} q_{j,s} + 1}, \forall j \in \mathcal{N}, \forall s \in \mathcal{S} \right\}. \quad (40)$$

Furthermore, when the prices of operators are coordinated, the total utility of operators is linearly decreasing with the price increasing. In order to achieve high utility of all operators, the prices of all operators decrease, and finally stop at the lowest boundary in (40). With different parameter θ_i , the price decreases with different tracks, thus stopping at different positions in the lowest boundary.

We would like to find an optimal $K_{i,s}$, $\forall i \in \mathcal{M}$, $\forall s \in \mathcal{S}$ to achieve the maximum value of W^{all} , given the sub-band allocation results. We set the second part of W^{all} as G , such as,

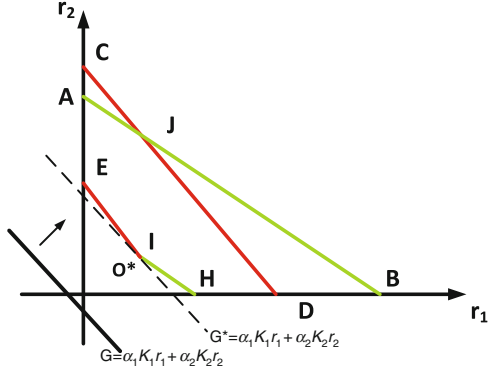
$$G = \sum_{i=1}^M \alpha_i K_{i,s} r_i. \quad (41)$$

Equation (41) is a hyperplane in the feasible region of prices. With G increasing from a small value, the distance between the hyperplane and the feasible region decreases. Ultimately, the hyperplane will cut through the feasible region. The first point O^* positioned $(r_1^*, r_2^*, \dots, r_M^*)$ in the feasible region achieves the lowest value of G , compared with all other points in the feasible region. In other words, O^* is the optimal point to achieve the maximum value of W^{all} . Correspondingly, the relationship of the prices follows

$$\theta_i = \frac{r_i^*}{r_1^*}. \quad (42)$$

To better understand this, we show the procedure in an example of two operators. Suppose there are two sub-bands in the unlicensed spectrum allocated to two UEs respectively. As shown in Fig. 8, the hyperplane is shown as $G = \alpha_1 K_{1,1} r_1 + \alpha_2 K_{2,2} r_2$. When G approaches G^* , the hyperplane goes through the first point O^*

Fig. 8 The optimal solution when operators are cooperative



in the feasible region. As the position of point O^* is (r_1^*, r_2^*) , r_1^* and r_2^* will be the optimal solution to achieve the maximum value of W^{all} . When the weight factors α_i in W^{all} are different, the position of the optimal point O^* may be different.

6 Simulation Results

We evaluate the performance of the proposed cooperative and non-cooperative scheme with MATLAB. We consider a hotspot circle area with a radius of 100 m. In the area, there are two operators, and each operator randomly deploys 2 SCBSs and 2 WAPs. We consider the uplink transmission and assume there are 100 UEs requesting service from the 20 sub-bands in the unlicensed spectrum. In order to avoid causing intolerably high interference to Wi-Fi users, we set the maximum transmit power of each UE in each time to be 2 W. We consider Additive White Gaussian Noise (AWGN) channels. Each sub-band in the unlicensed spectrum is 1 MHz, and the interference in each sub-band of the unlicensed spectrum for each UE is set as a random number with an average value of -20 dBm. The noise is assumed to be -30 dBm.

We first compare the performance of proposed cooperative and non-cooperative schemes with that of a single-operator scenario, where only one operator serves UEs in the unlicensed spectrum. As most existing resource management schemes in unlicensed spectrum assume a single-operator scenario, this comparison highlights the difference and advantages of our proposed strategies.

As shown in Fig. 9, we analyze the total utility of operators under different number of UEs. With an increasing number of UEs, the total utility of operators generally increases. In the proposed cooperative scheme, as the operators cooperate with each other, the total utility is the highest, followed by the non-cooperative scheme, where each operator makes decisions to maximize its own utility. Moreover, the total utilities in both the proposed cooperative and proposed non-cooperative schemes are higher than the total utility when there is only one operator in the scheme. In the single-operator cases, because of the limited number of WAPs, the total revenue received by the single operator is also limited.

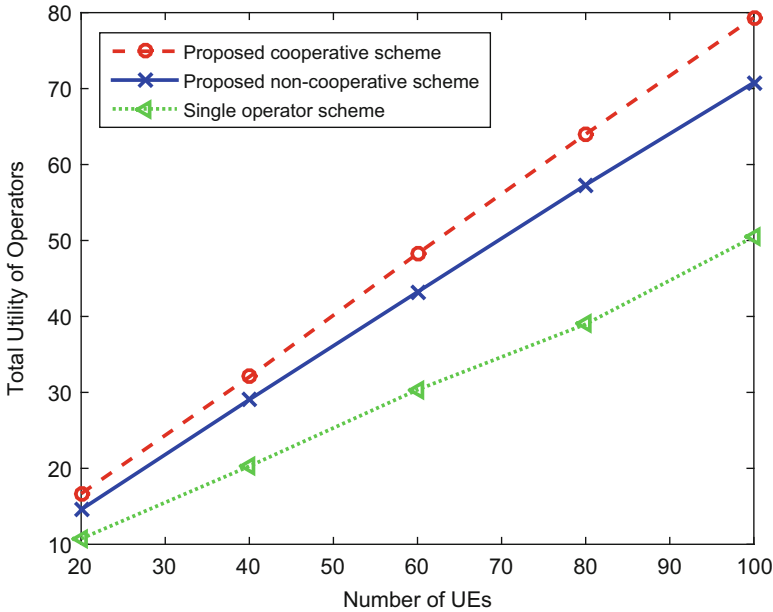


Fig. 9 The total utility of operators vs. the number of UEs

In Fig. 10, the total utility of UEs under different numbers of UEs is studied. When the number of UEs increases, the total utility of UEs increases. In the proposed cooperated scheme, because of the cooperation of operators, the service prices set by the operators are low, and each UE can be served with high quality of service at low prices. Thus, the total utility of UEs is the highest. In the single operator scheme, the operator is able to set low price to all UEs, while each UE can choose the SCBSs from different base stations for better performance and lower prices. Therefore, the total utility of UEs with single operator scheme is higher than the utility in the proposed non-cooperative schemes, but lower than the utility in the proposed cooperative scheme. In the proposed non-cooperative scheme, due to the competition among operators, the prices set by operators do not reach the lower bound. Thus the UEs pay more to the operators, and the total utility of UEs keeps the lowest.

In Fig. 11, we analyze the total utility of operators under different number of WAPs of each operator. When the number of WAPs of both operators increases, for each WAP, each UE is required to pay the interference penalty. However, in the proposed cooperative scheme and single operator scheme, in order to avoid losing UEs because of the high interference penalty, the operators are able to reduce the price. Thus, with the number of WAPs increasing, the total utility of operators in the proposed cooperative scheme and single operator scheme generally does not change, while the total utility of operators in the proposed cooperative scheme keeps higher than the utility of operator in the single operator scheme. Moreover, in the

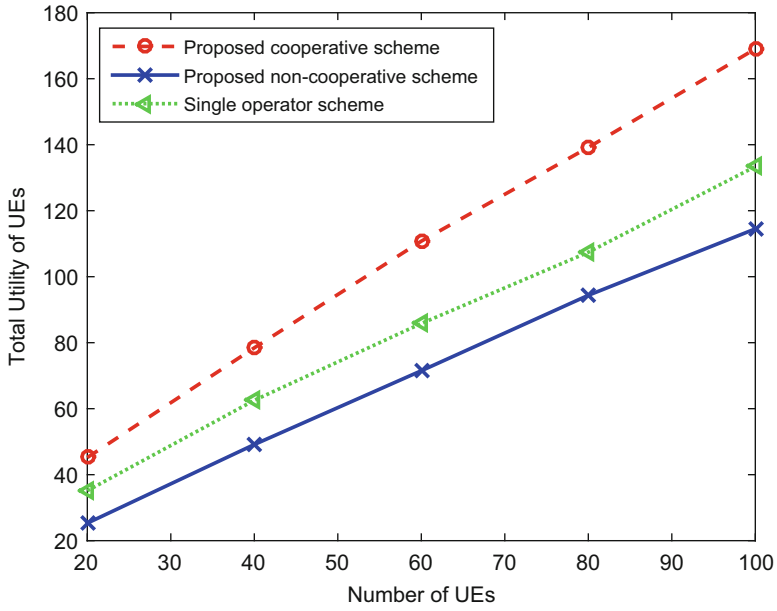


Fig. 10 The total utility of UEs vs. the number of UEs

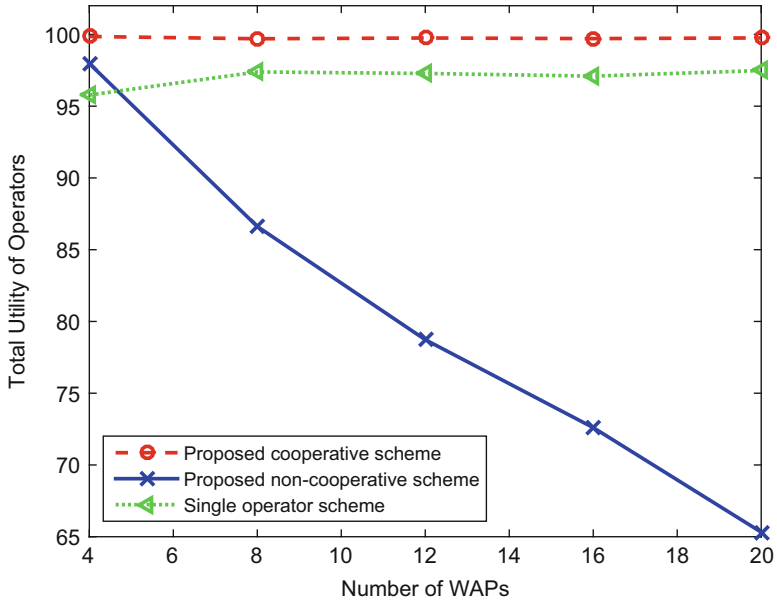


Fig. 11 The total utility of operators vs. the number of WAPs of each operator

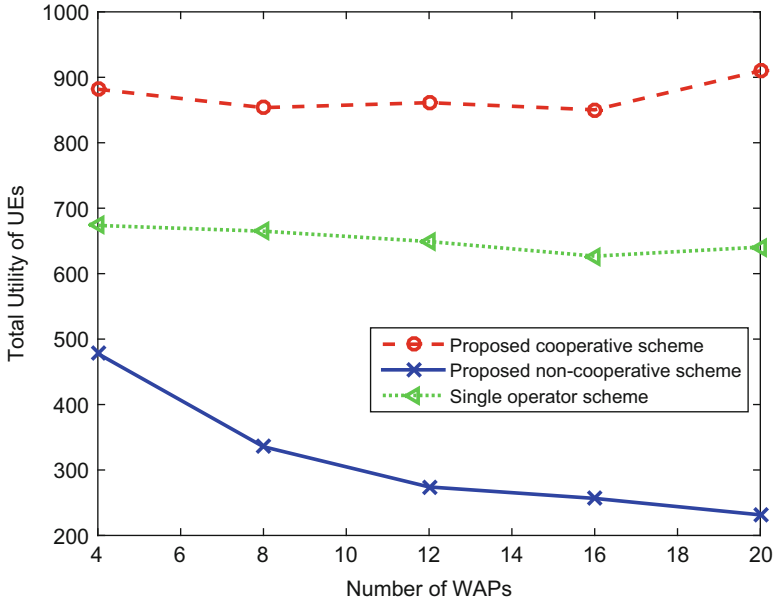


Fig. 12 The total utility of UEs vs. the number of WAPs of each operator

proposed non-cooperative scheme, because of the competition, each operator cannot reduce its price unilaterally to achieve higher utility. Thus, the prices set by operators keep in high value. Therefore, the total utility of operators in the proposed non-cooperative scheme is decreasing.

In Fig. 12, we investigate the total utility of UEs under different number of WAPs of each operator. When the number of WAPs of each operator increases, for each WAP, each UE is required to pay the interference penalty. However, in the proposed cooperative scheme and single operator scheme, as the operators are able to reduce the price in order to avoid losing UEs because of the high interference penalty, the total utility of UEs in the proposed cooperative scheme and single operator scheme generally does not change, while the total utility of UEs in the proposed cooperative scheme keeps higher than the utility of UEs in the single operator scheme. Moreover, in the proposed non-cooperative scheme, because of the competition, each operator is unable to reduce its price unilaterally to achieve higher utility. Thus, the prices set by operators keep in high value, and each UE is supposed to pay higher interference penalty with the number of WAPs increasing. Accordingly, the total utility of UEs in the proposed non-cooperative scheme is decreasing.

In Fig. 13, we evaluate the total utility of operators with different interference from Wi-Fi. As shown in the figure, when the interference from Wi-Fi increases, the utilities of some UEs may decrease to zero. Therefore, with a fewer UEs using the unlicensed spectrum, the total utility of operators decreases. Accordingly, the total utility generally decreases. Moreover, for the proposed non-cooperative scheme, the

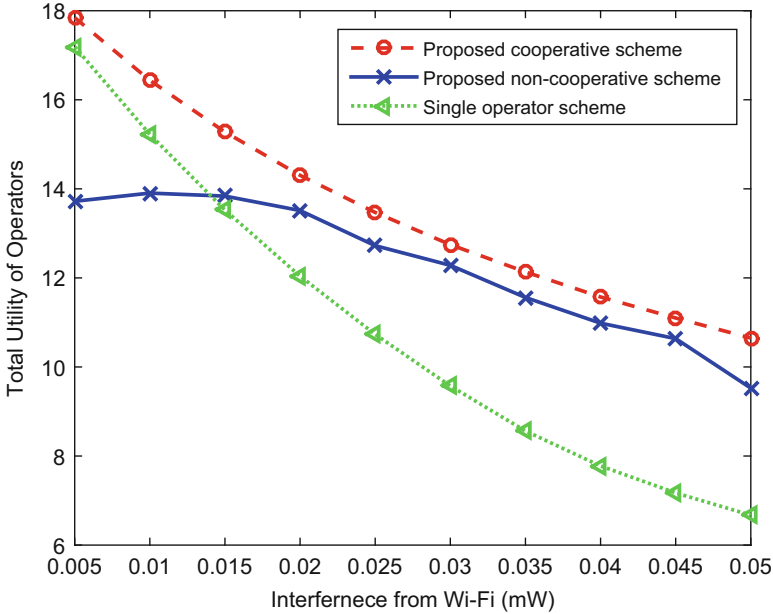


Fig. 13 The total utility of operators vs. the interference from Wi-Fi

total utility of operators first increases slightly then decreases. The reason is that when the interference from Wi-Fi is small, the prices set by some operators may be very high. With the interference from Wi-Fi, the operators are able to reduce their prices first to motivate the UEs to purchase services in the unlicensed spectrum, and thus the utility increases. However, when the price reduces to the lowest boundary, in order to guarantee the performance of Wi-Fi users, the operators cannot reduce their prices anymore, and the utilities of UEs gradually reduce and reach zero ultimately. Moreover, the total utility of operators in the proposed cooperative scheme is always larger than the utility of the operators in the proposed non-cooperative scheme and the utility of the operator in the single operator scheme. When the interference from Wi-Fi is small, the prices set by the operators are high in the proposed non-cooperative scheme. Thus, the total utility of operators in the proposed non-cooperative scheme is lower than the utility of the operator in the single-operator schemes. With the interference from Wi-Fi increasing, the prices set by the operators in the proposed non-cooperative scheme gradually decreases. Thus, the total utility of operators in the proposed non-cooperative scheme gradually surpasses the utility of operator in the single-operator schemes.

In Fig. 14, we analyze the relation between the total utility of UEs with different interference from Wi-Fi. Because of the strong interference from Wi-Fi, some UEs may receive zero utility and refuse to be served in unlicensed spectrum. Accordingly, the utilities of UEs generally decrease. However, in the proposed non-cooperative scheme, because the operators can reduce their prices to motivate the

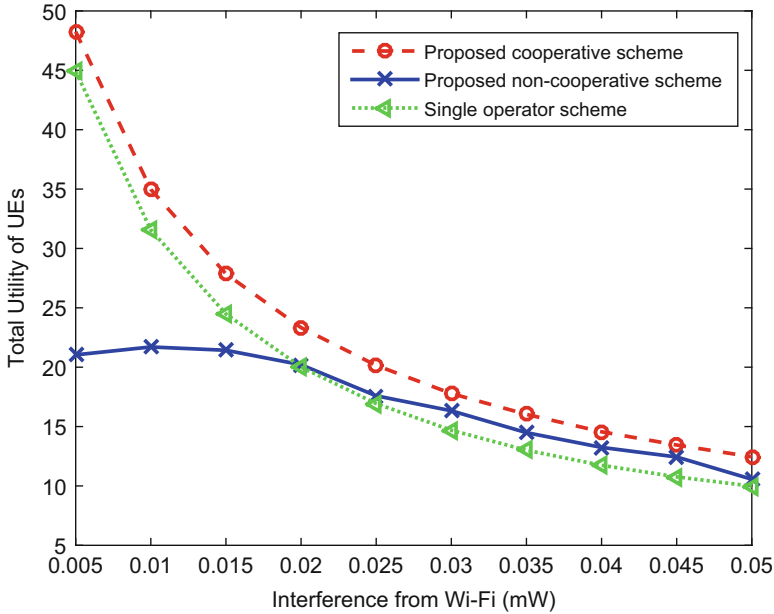


Fig. 14 The total utility of UEs vs. the interference from Wi-Fi

UEs in the unlicensed spectrum, the utility of UEs first increases then decreases. The total utility of UEs in the proposed cooperative scheme is always larger than the utility of the UEs in the proposed non-cooperative scheme and the utility in the single operator scheme. When the interference from Wi-Fi is small, the prices set by the operators are high in the proposed non-cooperative scheme. Thus, the total utility of UEs is lower than the utility of UEs in the single-operator schemes. With the interference from Wi-Fi increasing, the prices set by the operators in the proposed non-cooperative scheme gradually decreases. Thus, the total utility of UEs in the proposed non-cooperative scheme gradually surpasses the utility of UEs in the single-operator schemes.

In Fig. 15, we discuss the relationship between the total utility of operators and the maximum transmit power of UEs. With the maximum transmit power increasing, as operators are able to serve UEs with a lower price, the total utility of operators generally increases. When the maximum transmit power of UEs are relatively small, In the proposed cooperative and non-cooperative scheme, as the UE is able to choose operators with higher quality of service and lower price, the total utility of operators in the proposed cooperative scheme and in the proposed noncooperative scheme are always larger than the utility in the single-operator scheme. Furthermore, because of the competition of operators, the prices set by the operators in the proposed cooperative scheme are relatively smaller than the prices in the proposed non-cooperative scheme. Thus, the total utility of operators in the proposed cooperative scheme remains higher than the utility in the

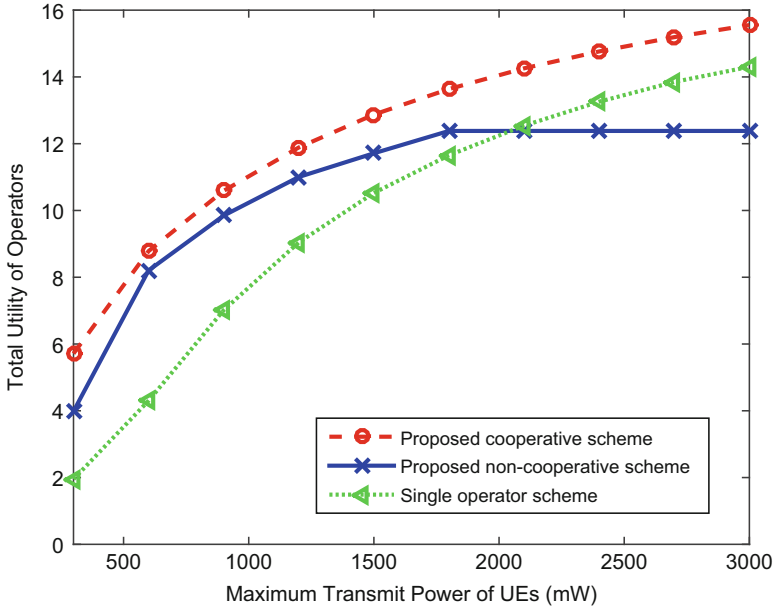


Fig. 15 The total utilities of operators vs. the maximum transmit power of UEs

proposed non-cooperative scheme. Moreover, with the maximum transmit power increasing, the feasible region increases. When the Nash equilibrium point of the non-cooperative scheme is no longer in the boundary of the feasible regions, the total utility of operators in the proposed non-cooperative scheme stops increasing and keeps unchanged. Therefore, when the maximum transmit power is large, with the maximum transmit power increasing, the total utility of operators in the single operator scheme surpasses the total utility of operators in the proposed non-cooperative scheme.

In Fig. 16, we analyze the relation between the total utility of UEs and the maximum transmit power of UEs. When the maximum transmit power increases, all UEs are able to transmit in high power, increasing the transmission rate during the service. Therefore, the total utility of all UEs generally increases. The total utility of UEs of the proposed cooperative scheme is always larger than that of the proposed non-cooperative scheme. Moreover, when the maximum transmit power is small, as the UE is able to choose operators with higher quality of service and lower price, the total utility of UEs in the proposed noncooperative scheme is larger than the utility in the single operator scheme. However, with the maximum transmit power increasing, the feasible region of in the Fig. 7 increases. When the Nash equilibrium point of the non-cooperative scheme is no longer in the boundary of the feasible regions, the total utility of UEs in the proposed non-cooperative scheme stops increasing and keeps unchanged. Therefore, when the maximum transmit power is large, with the

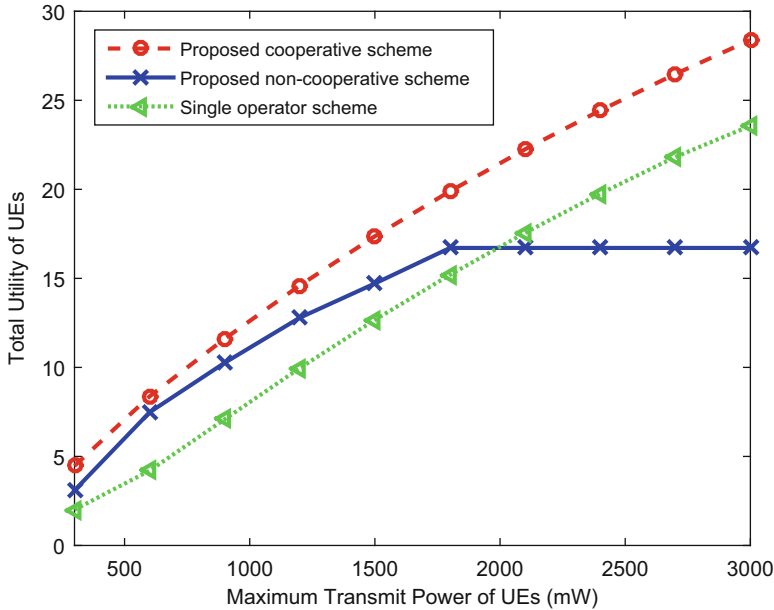


Fig. 16 The total utilities of UEs vs. the maximum transmit power of UEs

maximum transmit power increasing, the total utility of UEs in the single operator scheme surpass the total utility of UEs in the proposed non-cooperative scheme.

In Fig. 17, we fix the value of α_2 and increase α_1 to evaluate the total utility of operators with different ratio α_1/α_2 of weight factors. In the simulated scenario, the ratios of the weight factor α_1/α_2 can be divided into five sections, which means that the first intersection O^* of the hyperplane $G = \alpha_1 K_1 r_1 + \alpha_2 K_2 r_2$ and the feasible region fall in five different points based on different ratios of weight factor α_1/α_2 . Within five sections, when the ratio increases, the total weighted utility of operators increases.

In Fig. 18, we evaluate the utility of operator 2 when its price decreases in both the proposed cooperative and non-cooperative schemes. As shown in the figure, in the proposed cooperative scheme, as the prices of operators are linearly related, with the price of operator 2 decreasing, the utility of operator 2 increases monotonically. Furthermore, in order to guarantee the basic data transmission of Wi-Fi users, when the prices of all other operators keep unchanged, there is a lower bound for the price set by operator 2. Therefore, the optimal price of operator 2 is the price in the lowest boundary. However, in the proposed non-cooperative scheme, when the price of operator 2 decreases and the price of operator 1 remains unchanged, the utility of operator 2 first increases and decreases. Thus, the optimal price of operator 2 is not in the lowest boundary in the non-cooperative scheme, but in the middle of the feasible region.

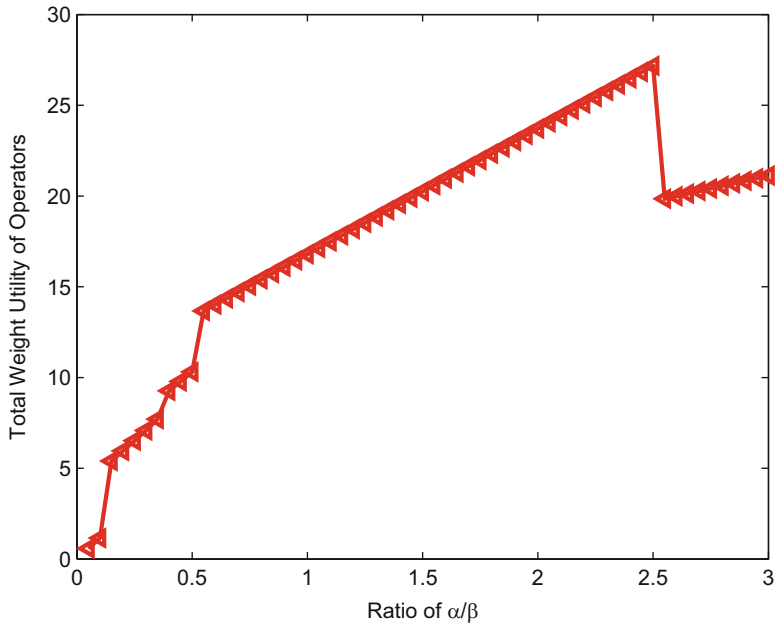


Fig. 17 The total utilities of operators vs. the ratio of weight factor

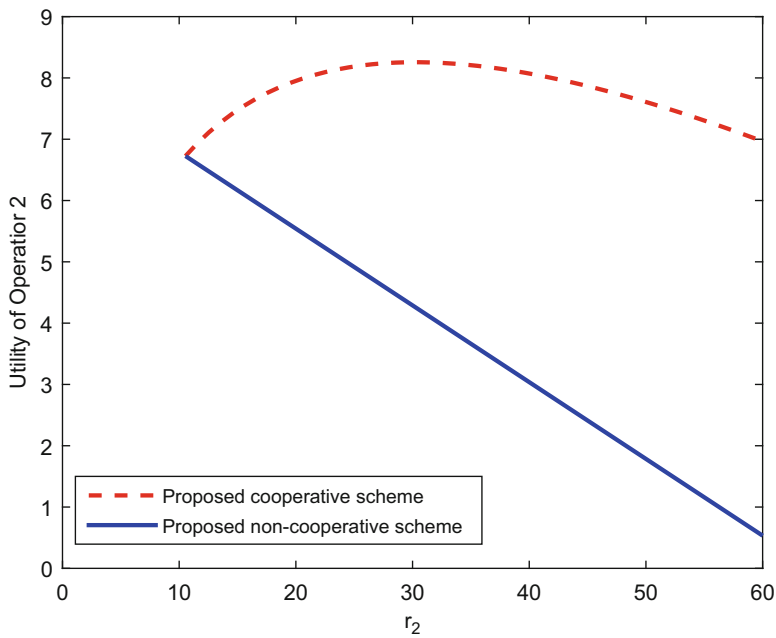


Fig. 18 The utility of operator 2 vs. price of operator 2

7 Summary

In this chapter, we have studied the power control mechanism among multiple cellular operators in the U-LTE in order to mitigate the interference management among multiple cellular operators and the unlicensed systems. A multi-leader multi-follower Stackelberg game has been formulated and both a cooperative and a non-cooperative schemes have been proposed for operators to achieve high revenues in U-LTE. In the non-cooperative scheme, each operator sets price rationally and independently based on the behaviors of others, and a sub-gradient algorithm has been adopted to achieve the highest utility. In the cooperative scheme, we have optimized the relations of the prices with a linear programming method so as to reach the highest utilities of all operators. Simulation results have shown that the operators in both the non-cooperative and cooperative schemes can significantly improve the utilities of all operators without causing intolerable interferences to unlicensed users, based on different network conditions in the unlicensed spectrum.

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