This is a repository copy of *Energy efficient and fair resource allocation for LTE-unlicensed uplink networks: A two-sided matching approach with partial information*.

White Rose Research Online URL for this paper:
http://eprints.whiterose.ac.uk/133455/

Version: Accepted Version

Article:

Gao, Y., Hu, H., Wu, Y. et al. (2 more authors) (2018) Energy efficient and fair resource allocation for LTE-unlicensed uplink networks: A two-sided matching approach with partial information. Transactions on Emerging Telecommunications Technologies, 29 (10). e3500. ISSN 2161-3915

https://doi.org/10.1002/ett.3500

© 2018 John Wiley & Sons, Ltd. This is an author produced version of a paper subsequently published in Transactions on Emerging Telecommunications Technologies. Uploaded in accordance with the publisher's self-archiving policy.

Reuse
Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown
If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

Energy Efficient and Fair Resource Allocation for LTE-Unlicensed Uplink Networks: A Two-sided Matching Approach with Partial Information

Yuan Gao[1], Haonan Hu[1],Yue Wu[2*], Xiaoli Chu[1] and Jie Zhang[1]

***Abstract*—LTE-Unlicensed (LTE-U) has recently attracted worldwide interest to meet the explosion in cellular traffic data. By using carrier aggregation (CA), licensed and unlicensed bands are integrated to enhance transmission capacity while maintaining reliable and predictable performance. As there may exist other conventional unlicensed band users, such as Wi-Fi users, LTE-U users have to share the same unlicensed bands with them. Thus, an optimized resource allocation scheme to ensure the fairness between LTE-U users and conventional unlicensed band users is critical for the deployment of LTE-U networks. In this paper, we investigate an energy efficient resource allocation problem in LTE-U coexisting with other wireless networks, which aims at guaranteeing fairness among the users of different radio access networks (RANs). We formulate the problem as a multi-objective optimization problem and propose a semi-distributed matching framework with a partial information-based algorithm to solve it. We demonstrate our contributions with simulations in which various network densities and traffic load levels are considered.**

***Index Terms*—LTE-Unlicensed, multi-objective optimization, one-to-many matching, incomplete preference list, matching theory.**

I. INTRODUCTION

The 1000x increase of data traffic is a major challenge for cellular networks in 5G networks [1]. To overcome the challenge, exploiting more spectrums for reliable communication is regarded as a promising solution. Industrial scientific and medical (ISM) radio bands, in particular, 5.8 GHz have attracted wide interest [2]. The overall available spectrum bandwidth in the unlicensed bands in major markets (e.g. US, Europe, China, Japan) is several hundred megahertz (MHz) [2].

LTE-unlicensed (LTE-U) is deployed to allow cellular user equipment (UE) to utilize ISM radio bands, in particular, 5.8 GHz. To enhance system capacity, unlicensed carriers are integrated into a cellular network by using the carrier aggregation (CA). The CA enables the aggregation of two or more component carriers into a combined bandwidth with one carrier serving as the Primary Component Carrier (PCC) and others serving as Secondary Component Carriers (SCCs) [3]–[5]. For LTE-U, licensed carrier serves as the PCC, while the unlicensed bands work as the SCCs in Time-Division-Duplexed (TDD) or Supplemental DL (SDL) only [2]. Furthermore, in [6], the authors proposed a mechanism that allowed device-to-device (D2D) communications operating in unlicensed bands utilizing LTE-U technologies.

Wi-Fi networks, with low cost and high data rates, have been the dominant players on all unlicensed bands in 2.4 and 5 GHz. However, spectrum efficiency in Wi-Fi systems is low, especially given the overloaded conditions. In contrast, LTE works more efficiently in terms of resource management and error control. Therefore, the deployment of LTE-U not only alleviates the spectrum scarcity of the cellular system, but also improves the spectrum efficiency on the unlicensed bands.

A. Challenges of Deploying LTE-U

Despite the huge potential to meet cellular traffic surges, LTE-U is still in its infancy; several deployment challenges remain to be overcome. First, Wi-Fi systems would experience significant performance degradation in the presence of LTE-U systems without a proper coexistence scheme [7], [8]. Wi-Fi systems employ carrier sense multiple access with collision avoidance (CSMA/CA) to access the unlicensed bands, and a Wi-Fi user will back off if the co-channel LTE-U signals is above the energy detection threshold (e.g., -62dBm over 20MHz) [9]. Therefore, a suitable coexistence mechanism is required in the LTE-U channel access scheme design. Secondly, LTE-U users may fail to meet its quality of service (QoS) requirement due to Wi-Fi transmission. What's more, the interference between LTE-U users of multiple operators would also lead to performance degradation of LTE-U users. Such unplanned and unmanaged deployment would result in severe performance degradation for both Wi-Fi and LTE-U networks and poor spectrum efficiency. LTE-U calls for coexistence schemes to enable harmonious resource sharing between Wi-Fi and LTE-U.

Thus, coexistence mechanisms have attracted substantial interest. Fair spectrum sharing between Wi-Fi and LTE-U can be ensured by using either non-coordinated or coordinated network managements. Non-coordinated schemes, such as LTE blank subframe allocation [10], listen-before talk (LBT) scheme [11], the carrier sense adaptive transmission (CSAT) by LTE-U forum [9], and 3 LBT schemes (Category (Cat) 2, 3, 4) by European Telecommunications Standards Institute (ETSI) [12], require modifications on the LTE-U side only, while coordinated schemes require information sharing about

---

[1] Yuan Gao, Haonan Hu, Xiaoli Chu and Jie Zhang are with the Department of Electronic and Electrical Engineering, The University of Sheffield, UK, e-mail: {ygao41, haonan.hu, x.chu, jie.zhang}@sheffield.ac.uk. [2] Yue Wu is with the School of Information Science and Engineering, East China University of Science and Technology, China, e-mail: {yuewu, zhuyu}@ecust.edu.cn.

[*] The Email of the corresponding author is: yuewu@ecust.edu.cn

network operations and spectral resources using centralized network interconnections, including cooperative control for spectrum access and managing coexistence using an X2 interface [13].

Research on the optimal resource allocation of the unlicensed spectrum has also been undertaken. Geometric programming [14] has been widely used in wireless communication to solve network resource allocation problems, which has been often used in LTE-U scenarios. In [15], the optimization performance of a hybrid method to perform both traffic offloading and resource sharing based on a duty cycle scheme is revealed. A fair-LBT (F-LBT) scheme is proposed by considering both the throughput and fairness of an LTE-U and a Wi-Fi system [16]. In [17], a matching-based student-project model is developed to guarantee unlicensed users QoS, together with the system-wide stability. Contention window size for both Wi-Fi and LTE-U users are jointly adapted to maximize LTE-U throughput while guaranteeing the Wi-Fi throughput threshold [18]. In [19], power allocation problem of the small base stations is formulated as a non-cooperative game by using a multi-framework. Fair proportional allocation is developed to optimize both Wi-Fi and LTE-U throughput [20]. A centralized joint power optimization and joint time division channel access optimization scheme is proposed to achieve significant gains for both Wi-Fi and LTE-U throughput [21]. A Nash bargaining game theoretic framework is also employed to solve the joint channel and power allocation problem in [22]. In [23], the unlicensed spectrum is divided into a contention period, for Wi-Fi users only, and a contention-free period, for LTE-U users. The optimal contention period is obtained by using the Nash bargaining solution. In [24], a joint user association and power allocation for licensed and unlicensed spectrum algorithm is proposed to maximize maximize sum rate of LTE-U/Wi-Fi heterogeneous networks.

Fair coexistence has not been defined clearly, and one of the definitions is that the deployment of an LTE-U system should not affect one Wi-Fi system more than another Wi-Fi system with respect to throughput and latency [2], [25]. Throughput fairness is explored by means of both α-fairness and max-min approach and time division access and channel sharing between Wi-Fi and LTE-U are found to be effective coexistence schemes. Moreover, a criterion for switching between these two schemes is also established in [26], subject to different network scenarios. We hold that a fair coexistence should consider both Wi-Fi and LTE-U users' QoS, such as throughput threshold and power consumption. Due to the limitations of power in end-user devices, if a user's throughput requirement were fulfilled by consuming an excessive amount of power, user's satisfaction would be affected. The ratio of the achievable user throughput to the consumed user energy, i.e., energy efficiency (EE), is an important indicator for wireless communications especially from a user's perspective, which has been widely explored in a 5G ultra-dense networks [27], cognitive radio [28], and OFDMA networks [29]. Therefore, it is interesting and critical to study the EE minimization problem in Wi-Fi and LTE-U coexistence scenarios while meeting their QoS requirements.

B. *Matching Theory Framework*

Matching theory is a mathematical framework for forming mutually beneficial relations, which was first applied in economics. It can be easily adapted to study resource allocation problems of a wireless communication system.

- Matching theory can model the interactions between two distinct sets of players with different or even conflicting interests [30]. For example, in an LTE uplink network, UE aims to achieve its QoS (mainly throughput) with minimal energy consumption while the objectives of small cell base stations (SCBSs) are serving users with certain QoS requirements and maximizing its capacity.
- Compared with game theory, a UE does not need other UEs' actions to make decisions. A preference list in terms of performance matrix, such as throughput and EE, is set up based on the local information including channel conditions. UEs made proposals according to this list. The only global information required from a centralized agent is the rejection/acceptance decision of each UE's proposal and blocking pair.

Recently, matching theory has emerged as a promising tool to cope with future wireless resource allocation problems. In a full duplex OFDMA network, UL and DL user pairing and sub-channel allocations are modelled as a one-to-one three-sided matching to maximize the sum system rate [31]. In [32], the decoupled uplink-downlink user association problem in multi-tier full-duplex cellular networks is formulated as two-sided many-to-one matching. An algorithm, based on a stable marriage algorithm is developed to find a near optimum with much lower complexity compared to a conventional coupled and decoupled user association scheme. A resource allocation problem for device-to-device (D2D) communications underlaying cellular networks is studied in [33]; a two-sided many-to-many matching scheme with an externality is proposed to find the sub-optimality. A matching based algorithm to study the resource allocation problem in an LTE-U scenario is proposed in [17]. The student-project model is used, in which students (cellular users) propose projects (unlicensed bands), and the decisions are made by lectures (base stations) to achieve maximal system (both LTE-U and Wi-Fi) throughput. Based on this paper, the same goal is studied by considering user mobility in [34]. However, all of the above work considers optimal system performance as a whole, instead of QoS (such as throughput) for each user. In addition, another limitation of the above works is that the matching is with complete preference lists. This is not always the case in the real world, for example, some bands may fail to achieve a user's QoS requirement, due to its availability and channel variation, which means that some bands are not acceptable to certain users, making the preference list incomplete.

C. *Contributions*

The major contributions of this paper are summarized as follows:

- Different from existing works, which typically consider only the fairness problem or overall EE (defined as the ratio of the overall data rate and the total energy

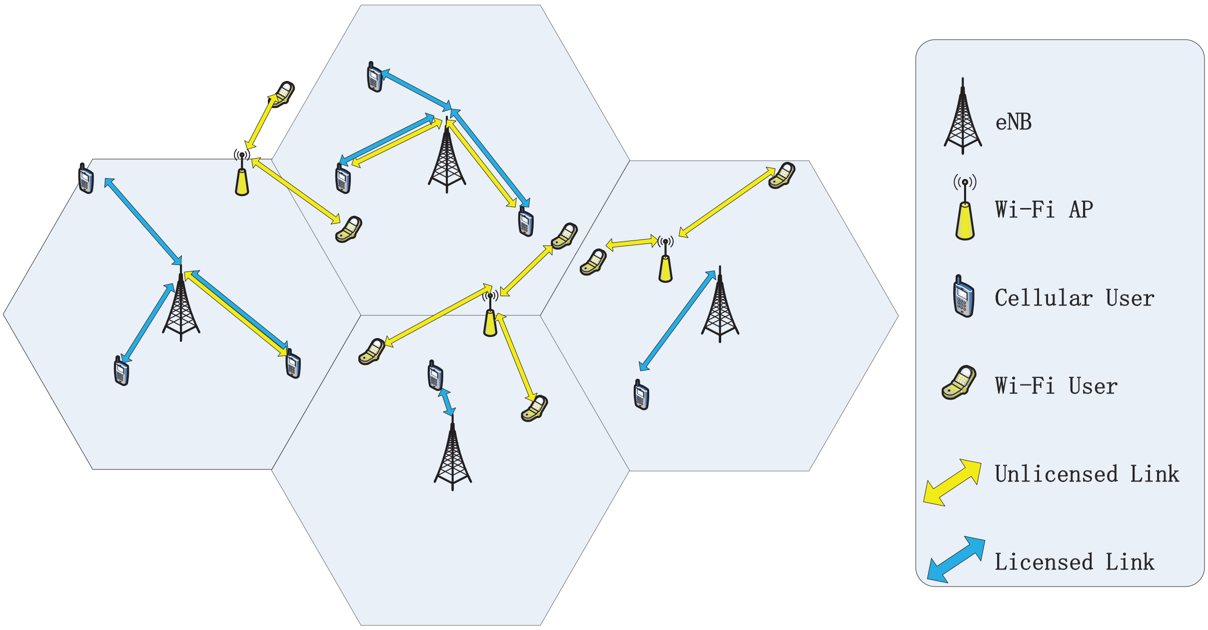

Fig. 1. System architecture of a LTE-U and Wi-Fi system

consumption), we propose an optimized shared scheme for LTE-U networks coexisting with Wi-Fi in ISM bands, which aims at maximizing the EE of independent LTE-U users while guaranteeing fairness among different users. That is, the proposed algorithm would guarantee the QoS requirement for each user (including CUs and Wi-Fi users).

- The optimization problem is formulated as a *multi-objective optimization problem*, in which typically a set of Pareto solutions can be achieved. We utilize the weighted sum method to transform the multi-objective optimization problem into a *single-objective optimization problem* and find the Pareto optimal solution.
- The single-objective optimization problem can be further modelled as a one-to-many matching game with partial information. Here *partial information* means *incomplete preference lists*, which is due to the fact that some UBs fail to fulfil a user's minimal throughput requirement and are not acceptable to that user. Such problem has not yet been solved. We propose a semi-distributed two-step stable algorithm to solve it. Numerical results demonstrate that the proposed algorithm can achieve good performance with fast convergence speed.

The rest of the paper is organized as follows. The system model is described in Section III. The problem formulation from a multi-objective optimization to a single-objective formulation is developed in IV. To solve the optimization problem, a two-step matching-based resource allocation and user association algorithm are proposed in Section V. In Section VI, numerical results are presented and analysed. Section VII concludes the paper.

II. SYSTEM MODEL

As shown in Fig. 1, we consider a LTE-U network coexisting with a Wi-Fi network in ISM bands (e.g. 2.4 and 5.8 GHz), composed of M independently uniformly distributed small-cell base stations (SCBSs), $SCBS = \{SCBS_1, ...SCBS_m, ...SCBS_M\}$, and N independently uniformly distributed Wi-Fi access points (APs), $AP = \{AP_1, ...AP_n, ...AP_N\}$. All the SCBSs are deployed by the same cellular network operator. K cellular users (CUs), $CU = \{CU_1, ...CU_k, ...CU_K\}$ and N' Wi-Fi users (WU), $WU = \{WU_1, ...WU_{n'}, ...WU_{N'}\}$ are uniformly distributed in the area of interest.

As shown in Fig. 2, the whole unlicensed spectrum is divided into U orthogonal UBs. Then in the time domain, each UB is divided into slots; the period of a slot is T. Each slot consists of several sub-frames, the duration of a subframe is t, which is smaller than the coherence time of the signal channel. Thus, during the transmission period of a sub-frame, the power attenuation caused by Rayleigh fading in each link can be regarded as a fixed parameter. Moreover, each subframe is considered strictly independent.

WUs communicate with Wi-Fi APs under a standard carrier sense multiple access protocol with collision avoidance (CSMA/CA). CUs are served by SCBSs by using a licensed band for both uplink and downlink transmission, while they seek to aggregate unlicensed bands for a supplementary uplink transmission.

A CU can access its local SCBS for uplink transmission with one of U UBs. We consider LTE-U using a duty cycle scheme to manage the coexistence in the unlicensed spectrum in the time domain. By using this duty cycle method, CUs will use a almost blank subframe (ABS) pattern [10] to guarantee Wi-Fi QoS by muting a fraction of time for UB_u. The fraction l_u will be adaptively adjusted based on the Wi-

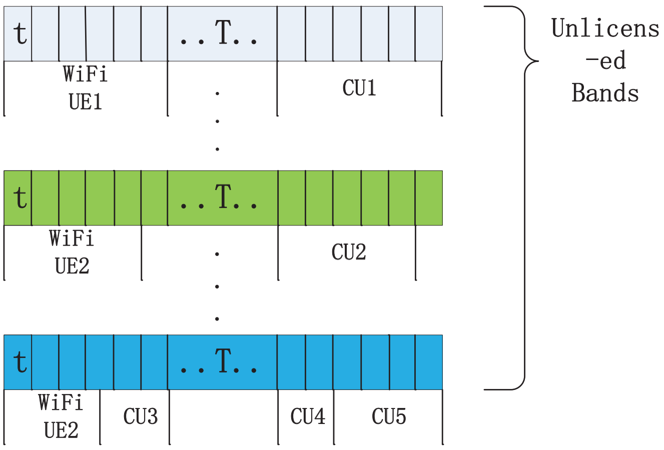

Fig. 2. TDD sharing of unlicensed bands between Wi-Fi and LTE-U users

TABLE I
GENERAL NOTATION

$SCBS_m$	the mth small cell base station
AP_n	the nth access point
CU_k	the kth cellular user
UB_u	the uth unlicensed band
T	slot time
t	sub-frame time
l_u	the fraction of time LTE-U is muting on UB_u
$C^C_{k,m,u}$	the uplink capacity CU_k associating with $SCBS_m$ on unlicensed band UB_u
$I_{k,m,u}$	the number of sub-frames in UB_U allocated to CU_k served by $SCBS_m$
$C_{k,m,u,i}$	the achievable data rate of CU_k served by$SCBS_m$
$\chi_{k,m,u}$	equals 1 if CU_k is served by $SCBS_m$ using UB_u
$P^{CU}_{k,m}$	transmission power from CU_k to $SCBS_m$
$g_{k,m,u}$	channel power gain between CU_k and $SCBS_m$ on UB_u
$R_{k,m,u}$	the uplink throughput of CU_k served by $SCBS_m$ on UB_u
σ^2_N	the thermal noise
WU_u	Wi-Fi users on UB_U
R^W_u	throughput requirement of WU_u
PE^{CU}_k	energy efficiency of CU_k
R^L_k	Throughput requirement of CU_k

Fi data requirement. Here, we consider the static synchronous muting pattern.

The notations in this paper can be found in Table I.

A. LTE-U Throughput

During the transmission slot of LTE-U, we denote the uplink capacity $C^C_{k,m,u}$ of k-th CU CU_k associating with $SCBS_m$ on unlicensed band UB_u. Thus, the uplink throughput on UB_u is given by:

$$R^{CU}_{k,m,u} = \sum_{i=1}^{I_{k,m,u}} C^{CU}_{k,m,u,i}, \tag{1}$$

where $I_{k,m,u}$ is the number of sub-frames in UB_U allocated to CU_k served by $SCBS_m$. $C_{k,m,u,i}$ is the achievable data rate of CU_k served by $SCBS_m$ the u-th sub-frame of UB_u, given as:

$$C^{CU}_{k,m,u,i} = t_i B_u log_2(1 + \frac{\chi_{k,m,u} P^{CU}_{k,m} g_{k,m,u}}{\sigma^2_N + \sum_{j \neq k}^{K} \sum_{m}^{M} \rho_{j,m,u} P^{CU}_{j,m} g_{j,m,u}}) \tag{2}$$

where, $\chi_{k,m,u}$ is an indicator function, defined as:

$$\chi_{k,m,u} = \begin{cases} 1, \text{ if } CU_k \text{ is served by } SCBS_m \text{ using } UB_u, \\ 0, \text{ otherwise.} \end{cases} \tag{3}$$

$P^{CU}_{k,m}$ represents the transmission power from CU_k to $SCBS_m$. $g_{k,m,u}$ is the channel power gain between CU_k and $SCBS_m$ on UB_u, and $g_{j,m,u}$ is the channel gain between CU_j and $SCBS_m$ on UB_u. σ^2_N is the thermal noise.

B. Wi-Fi Throughput

For each WU $WU_{n'}$, there is equal probability of accessing one of the unlicensed bands. We regard the WUs sharing the same UB as one WU, the interactions between co-channel CUs and WUs can be simplified to the interactions between co-channel CUs and a WU [17], [34]. The WU that occupies UB_u is denoted as WU_u. Thus, the throughput of Th_u can be expressed by [35]:

$$Th_u = \frac{\overline{E(p)} P^u_{tr} P^u_s}{(1 - P^u_{tr})\delta + P^u_{tr} P^u_s T_s + P^u_{tr}(1 - P^u_s) T_c}, \tag{4}$$

where $\overline{E(p)}$ is the average packet size of Wi-Fi transmission, P^u_{tr} is the probability that UB_u is occupied, and P^u_s is the successful transmission probability in UB_u. δ is the slot time defined in 802.11. T_s and T_c are the average time consumed by a successful transmission and a collision in UB_u, respectively.

Based on the ABS scheme, the fraction of time slots l_u of UB_u will be allocated to the WU_u using UB_u. To guarantee throughput requirement R^W_u of WU_u, l_u is given as

$$Th_u l_u T \geq R^W_u. \tag{5}$$

III. PROBLEM FORMULATION

We define the EE of CU_k, i.e., the throughput of CU_k obtained per unit power consumption with the unit of $'bits-per\jmath oule'$ [28] as follows:

$$PE^{CU}_k = \frac{\sum_m^M \sum_u^U \chi_{k,m,u} R_{k,m,u}}{\sum_m^M \sum_u^U \chi_{k,m,u} I_{k,m,u} P^{CU}_{k,m}} \tag{6}$$

We formulate the following EE maximization problem for each CU as a multi-objective optimization problem:

$$min(-PE_1^{CU}, ..., -PE_K^{CU}), \tag{7}$$

$$s.t$$

$$\sum_k^K \sum_u^U \chi_{k,m,u} \leq 1, \, m \in \{1, ..., M\}, \tag{7a}$$

$$\sum_m^M \sum_u^U \chi_{k,m,u} I_{k,m,u} t \leq Tl_u, \quad k \in \{1, ..., K\}, \tag{7b}$$

$$\chi_{k,m,u} \in \{0,1\}\,, \, k \in \{1, ..., K\}, m \in \{1, ..., M\}, \quad u \in \{1, ..., U\}, \tag{7c}$$

$$P_{k,m}^{CU} \leq P_{max}, \, k \in \{1, ..., K\}, m \in \{1, ..., M\}, \tag{7d}$$

$$Th_u(l_u)T \geq R_u^W, \, u \in \{1, ..., U\}, \tag{7e}$$

$$\sum_m^M \sum_u^U \chi_{k,m,u} R_{k,m,u} \geq R_k^L, \, k \in \{1, ..., K\}. \tag{7f}$$

where, constraint (7a) indicates that a CU can be allocated up to 1 UB at a time. (7b) is the limitation of the available resource of each UB for LTE-U transmission. In (7c), $\chi_{k,m,u}$ is a binary number, equal to 1 if CU_k served by $SCBS_m$ on UB_u, or 0 otherwise. The transmission power limit of each CU is set in (7d). The throughput minimum requirement of each Wi-Fi user and CU is shown in (7e) and (7f), respectively.

The general technique used to solve the multi-objective optimization is a weighted-sum or scalarization method by transforming a multi-objective function into a single-objective function [36] as:

$$min(-\sum_{k=1}^K \gamma_k PE_k^{CU}), \tag{8}$$

$$s.t$$

$$\sum_{k=1}^K \gamma_k = K, \tag{8a}$$

$$\sum_k^K \sum_u^U \chi_{k,m,u} \leq 1, \, m \in \{1, ..., M\}, \tag{8b}$$

$$\sum_m^M \sum_u^U \chi_{k,m,u} I_{k,m,u} t \leq Tl_u, \quad k \in \{1, ..., K\}, \tag{8c}$$

$$\chi_{k,m,u} \in \{0,1\}\,, \, k \in \{1, ..., K\}, m \in \{1, ..., M\}, \quad u \in \{1, ..., U\}, \tag{8d}$$

$$P_{k,m}^{CU} \leq P_{max}, \, k \in \{1, ..., K\}, m \in \{1, ..., M\}, \tag{8e}$$

$$Th_u(l_u)T \geq R_u^W, \, u \in \{1, ..., U\}, \tag{8f}$$

$$\sum_m^M \sum_u^U \chi_{k,m,u} R_{k,m,u} \geq R_k^L, \, k \in \{1, ..., K\}. \tag{8g}$$

The effectiveness of the transformations is given in $Lemma$ 1 [36] as:

Lemma 1. *The single-objective minimizer is an effective solution for the original multi-objective problem. If the γ_k weight vector is strictly greater than zero, then the single-objective minimizer is a strict Pareto optimum.*

where strict Pareto optimum is defined as follows:

Definition 1. *Strict Pareto Optimum: A solution Matrix **M** is said to be a strict Pareto optimum or a strict efficient solution for the multi-objective problem (7) if and only if there is no $m \subseteq S$ such that $PE_k^{CU}(m) \leq PE_k^{CU}(m')$ for all $k \in 1, ..., K$, with at least one strict inequality. S is the constraints (7a-7f).*

If all the CUs are of the same priority, i.e.,

$$\gamma_k = 1, k \in \{1, ..., K\}. \tag{9}$$

The EE optimization is finally transformed into:

$$min(-\sum_{k=1}^K PE_k^{CU}), \tag{10}$$

$$s.t$$

$$\sum_k^K \sum_u^U \chi_{k,m,u} \leq 1, \, m \in \{1, ..., M\}, \tag{10a}$$

$$\sum_m^M \sum_u^U \chi_{k,m,u} I_{k,m,u} t \leq Tl_u, \quad k \in \{1, ..., K\}, \tag{10b}$$

$$\chi_{k,m,u} \in \{0,1\}\,, \, k \in \{1, ..., K\}, m \in \{1, ..., M\}, \quad u \in \{1, ..., U\}, \tag{10c}$$

$$P_{k,m}^{CU} \leq P_{max}, \, k \in \{1, ..., K\}, m \in \{1, ..., M\}, \tag{10d}$$

$$Th_u(l_u)T \geq R_u^W, \, u \in \{1, ..., U\}, \tag{10e}$$

$$\sum_m^M \sum_u^U \chi_{k,m,u} R_{k,m,u} \geq R_k^L, \, k \in \{1, ..., K\}. \tag{10f}$$

We denote the solution for optimization problem (10) as Matrix ***M***, which, according to Lemma. 1, is an strict Pareto optimum for the multi-objective optimization problem (7).

In the expression of PE_k^{CU}, which is nonlinear, $I_{k,m,u}$ and $\chi_{k,m,u}$ are integers, while $R_{k,m,u}$ and $P_{k,m}^{CU}$ are continuous variables. The objective function (10) is a summation of $PE_k^{CU}, k \in \{1, ..., K\}$, thus, it is a mixed integer nonlinear programming (MINLP) problem, which is typically NP-hard. Thus, to reduce the computation complexities, we developed a matching-based solution, which will be discussed in the following section.

IV. MATCHING WITH INCOMPLETE PREFERENCE LISTS

A. Introduction to Matching Theory and Student-Project-Allocation Problem

Student project allocation (SPA) is a one-to-many matching game, where each student has a preference list of the projects that they can choose from, while the lecturers have a preference list of students for each project or a preference list of student-project pairs. There is an upper bound, also known as the quota, on the number of students that can be assigned to each particular project [37].

Inspired by the SPA problem, we model the resource allocation problem in (10) as an SPA game, where the CUs, UBs and SCBSs are considered equivalent to students, projects and lecturers, respectively. Similarly, SCBSs offer the set of available UBs and maintain a preference list for each UB, and each CU has a preference list of UBs that they can use for uplink transmission. SCBSs allocate UBs to CUs based on the achievable EE on UBs. Meanwhile, our resource allocation problem differs from the SPA game in the following aspects:

- **Maximum throughput**: The quota in the SPA problem is replaced by the maximum achievable throughput of a UB. The maximum achievable throughput of a UB determines the maximum number of CUs that it can be allocated to while meeting the minimum required Wi-Fi throughput in the TDD mode.
- **Incompleteness of preference lists**: The SCBSs sense the availabilities of and keep the CUs updated. Any UB that is not able to fulfil a CU's minimal throughput requirement will be deleted from the preference list of the CU and the CU will be removed from the preference list of that UB. Only a subset of UBs (CUs) are in the preference list of a CU (UB), i.e., the preference lists are incomplete.

The *k*th CU preferring the *u*th UB over the *u*'th UB is denoted by $pri(CU_k, UB_u) > pri(CU_k, UB_{u'})$. Similarly, $pri(UB_u, CU_k) > pri(UB_u, CU_{k'})$ indicates that the *u*th UB prefers the *k*th CU over *k*'th CU. The one-to-many matching is defined as follows:

Definition 2. *Let μ denote the one-to-many matching between two disjoint sets **CU** and **UB**.*

$\mu(CU_k) = UB_u$ indicates that the kth CU is matched to the uth UB,

$\mu(UB_u) = \{CU_k, ..., CU_{k'}\}$ indicates that the uth UB is matched to $\{CU_k, ..., CU_{k'}\}$,

$\mu(CU_k) = CU_k$ indicates that the kth CU is not really matched to any UB.

The stability implies the robustness of the matching against deviations caused by the individual rationality of players, i.e., the CUs in our resource allocation problem. In an unstable matching, two CUs may swap their matched UBs to maximize their own EE, leading to an undesirable and unstable resource allocation. The definition of stability of the one-to-many matching is given as follows:

Definition 3. *Stability of One-to-Many Matching. The one-to-many matching μ between two disjoint sets **CU** and **UB** is stable, only if it is not blocked by any blocking individual or blocking pair, where the blocking individual and the blocking pair are defined in the following.*

Blocking individual in the EE optimization problem is defined as:

Definition 4. *Blocking Individual. A CU is a blocking individual if it prefers to stay unmatched rather than being matched to any available UB.*

The blocking pair in the EE optimization problem is defined as:

Definition 5. *Blocking Pair. A pair (CU_k, UB_u) is a blocking pair if all the following 3 conditions are satisfied:*

(1) $\mu(CU_k) \neq UB_u$ and $pri(CU_k, UB_u) > pri(CU_k, \mu(CU_k))$;

(2) $\mu(UB_u) \neq CU_k$ and $pri(UB_u, CU_k) > pri(UB_u, \mu(UB_u))$;

(3) There is enough spectrum in UB_u to meet the minimum throughput requirement of CU_k.

B. Preference Lists of CUs Over UBs

We assume that the preference of CU_k over UB_u is based on EE $PE^{CU}_{k,m,u}$ achieved by CU_k served by $SCBS_m$ using UB_u to guarantee its QoS threshold, which is written as follows:

$$PE^{CU}_{k,m,u} = \frac{\sum_m^M \sum_u^U \chi_{k,m,u} R_{k,m,u}}{\sum_m^M \sum_u^U \chi_{k,m,u} P^{CU}_{k,m} I_{k,m,u} t} \tag{11}$$

CU_k prefers UB_u over $UB_{u'}$ if CU_k can achieve higher EE using UB_u than $UB_{u'}$, which is stated as follows:

$$pri(CU_k, UB_u) > pri(CU_k, UB_{u'}) \Leftrightarrow PE^{CU}_{k,m,u} > PE^{CU}_{k,m,u'} \tag{12}$$

None of the CUs have any knowledge about other co-channel coexisting CUs, before the final band allocation is performed at SCBSs. Thus, the preference lists are set up based on local channel sensing information and unlicensed band availability alone.

C. Preference Lists of SCBS Over (CU_k, UB_u) Pair

However the preference of $SCBS_m$ over the user-band pair (CU_k, UB_u) is based on the EE achieved by allocating UB_u to CU_k to fulfil the QoS threshold of CU_k. It is written as $SCBS_m$ prefers CU_k over $CU_{k'}$ to occupy UB_u if CU_k can achieve higher EE than $CU_{k'}$ by using UB_u, which is stated as follows:

$$pri(UB_u, CU_k) > pri(UB_u, CU_{k'}) \Leftrightarrow PE^{CU}_{k,m,u} > PE^{CU}_{k',m,u} \tag{13}$$

D. Two-Step Algorithm

1) Step 1: Modified GS Algorithm for One-to-Many Game: To solve the above matching game, a 2-step algorithm is proposed. The first step is an extension of the GS algorithm applied for a one-to-many matching with incomplete preference lists. Each iteration begins with the unmatched CUs proposing their favourite (i.e., the first UB) UB on their current preference lists. The UBs which have been proposed to will be removed from the CUs' preference lists. For each UB_u, SCBSs decide whether to accept or reject the CU's proposal UB_u based on SCBSs' preference lists over (CU_k, UB_u) pairs. SCBSs choose to keep the most preferred CUs as long as these CUs do not occupy more resources than the UB could offer; the remaining CUs are rejected. Such a procedure runs until every CU is either matched or its preference list is empty. The implementation detail of Step 1 of the algorithm is stated in A1 as follows:

Theorem 1. *Stability of μ_1. In any instance of one-to-many matching, stable matching is achieved by using A1.*

Proof: We prove this theorem by contradiction and assume that for an instance of one-to-many matching, A1 terminates with an instable matching μ_1, i.e., there exists at

Algorithm A1 One-to-Many Matching

```
Input: $CU$, $UB$, $PL^{CU}$, $PL^{UB}$
Output: Matching $\mu_1$
Step 1 Proposing
    All free $CU_k$ propose their favourite $UB_u$ in their preference lists, and remove $UB_u$ from the list.
Step 2 Accepting/rejecting
    $UB_u$ accept the most preferred $n$ proposers based on its preference list, the rest are rejected. The sum of the slot time of the accepted proposers does not exceed its available resource time.
    None of the accepted proposers are free.
    All the rejected proposers are free.
Criterion
    If every CUs is either allocated with a UB or its preference list is empty, this algorithm is terminated with an output $M_1$.
    Otherwise, Step 1 and Step 2 are performed again.
```

least one blocking pair (CU_k, UB_u) or one blocking individual CU_k.

If there exists one blocking pair (CU_k, UB_u) in μ_1:

- Case 1: In μ_1, UB_u is unmatched and CU_k is matched with UB'_u. If UB_u is not on the preference list of CU_k, then, CU_k does not have an incentive to match with UB_u; If $pri(CU_k, UB_{u'}) > pri(CU_k, UB_u)$, and CU_k is matched with UB'_u in μ, then CU_k does not have an incentive to match with UB_u; If $pri(CU_k, UB_u) > pri(CU_k, UB_{u'})$, then CU_k proposes to UB_u before $UB_{u'}$. CU_k is rejected during the proposal stage or is accepted by UB_u first, then is rejected. In conclusion, in any situation in which CU_k is matched and UB_u is unmatched, a blocking pair does not exist.
- Case 2: In μ_1, UB_u being unmatched and CU_k unmatched. UB_u is unmatched means that it receives no proposal from CU, including CU_k. This means that UB_u is not on $CU'_k s$ preference list, then CU_k does not have incentive to match with UB_u. In conclusion, in any situation in which both CU_k and UB_u are unmatched, blocking pair does not exist.
- Case 3: In μ_1, UB_u being matched with CU'_k and CU_k unmatched. CU_k is unmatched means that either it has no UB_u in its preference list, or all its proposals have been rejected. For the former, CU_k does not have an incentive to match with UB_u. For the latter, UB_u rejects CU_k because it prefers other proposer(s). Thus, UB_u does not have an incentive to match with CU_k. In conclusion, in any situation in which both CU_k is unmatched and UB_u is matched, blocking pair does not exist.
- Case 4: In μ_1, UB_u is matched with CU'_k and CU_k with UB'_u. UB_u must be on CU'_ks preference list, and vice versa, otherwise, there is no incentive to form the (CU_k, UB_u) pair. If $pri(CU_k, UB_{u'}) > pri(CU_k, UB_u)$, then, CU_k does not have an incentive to match with UB_u if it is matching with $UB_{u'}$. If $pri(CU_k, UB_u) > pri(CU_k, UB_{u'})$, then, CU_k proposes to UB_u first and is rejected, because UB_u prefers CU'_k to CU_k, then UB_u does not have an incentive to match with CU'_k. In conclusion, in any situation in which both CU_k and UB_u are matched, a blocking pair does not exist.

Contradictions, as (CU_k, UB_u) is any pair, thus, it could be said that there is no blocking pair in matching μ_1.

If one blocking individual CU_k or UB_u exists in μ_1:
for blocking individual CU_k:

- Case 1: In μ_1, CU_k is matched with UB_u, i.e., UB_u is on CU_k's preference list, as such CU_k does not have incentive be unmatched. In conclusion, in any situation in which both CU_k and UB_u are unmatched, blocking individual CU_k does not exist.

The proof that blocking individual UB_u does not exist is similar to that blocking individual CU_k does not exist.

As the above blocking pair (CU_k, UB_u), blocking individuals CU_k or UB_u can be any pair or individual, thus, we could prove that there is no blocking pair or blocking individual in matching μ_1. ■

Theorem 2. *Praeto optimality of μ_1.*
In any instance of one-to-many matching, stable matching μ_1 achieved by A1 is Praeto optimal, i.e., no player(s) can better off, whilst no players are worse off.

Proof: In stable matching μ_1:

- Case 1: There exists an unmatched CU_k, which can be matched to UB_u to increase the achievable EE of both CU_k and UB_u, meaning that (CU_k, UB_u) is the blocking pair of matching μ_1, contracting **Theorem 1**.
- Case 2: There exists a (CU_k, UB_u) pair. Obviously, CU_k does not have an incentive to be unmatched; CU_k has the incentive to change partner from UB_u to $UB_{u'}$ to increase its achievable EE, meaning that (CU_k, $UB_{u'}$) is a blocking pair of matching μ_1, contracting **Theorem 1**.

It is impossible to increase the EE of some CUs' without decreasing that of the remaining of the CUs. The state stands for UB, which can be proven similarly as above. ■

We define the computational complexity of A1 as the number of accepting/rejecting decisions required to output a stable matching μ_1. The complexity of A1, i.e., the convergence of A1 is given in **Theorem 3**.

Theorem 3. *Complexity of A1 (Convergence of A1). In any instance of many-to-one matching, a matching μ_1 can be obtained by using A1 within $\mathcal{O}(KU)$ iterations.*

Proof: In each iteration, a CU proposes to its most favourite UB in its current preference list, and SCBS accepts/rejects the proposal. The maximum number of elements in the preference list of CU_k equals the number of UBs, i.e., U. Thus, stable matching μ_1 can be obtained in $\mathcal{O}(KU)$ overall time, where K is the number of CUs and U is the number of UBs. ■

2) Step 2: EE Optimization: As proven above, stability and Pareto optimality have been guaranteed by using algorithm A1, meaning that there are no incentives for any CUs and UBs to form new matching. However, the preference lists of CUs could to be incomplete, some CUs may be unmatched [38], [39].

To further maximize system's EE by increasing the number of CUs matched by algorithm A2, an iteration of algorithm A2 begins with an unmatched CU_k proposing to its most favourite UB_u, and UB_u would be deleted from the preference list of CU_k. An SCBS would consider this proposal acceptable if the following criteria are fulfilled:

- After deleting several non-favourites or all CUs matched with UB_u in μ_1 obtained via algorithm A1, the minimal throughput of CU_k can be achieved by using UB_u
- All the deleted CUs could be served by other UBs to fulfil their minimal throughput requirement.
- The EE of the new matching μ_k is greater than that of the previous matching μ_1.

Such matching μ_k would be considered as a profitable reallocation, and would be updated as the new matching, if only one profitable reallocation exists. Should there be multiple profitable reallocations, the one that enhances the overall EE the most would be the new matching. The iterations would run several times, until every CU is either allocated with a UB or its preference list is empty. The detail of algorithm A2 is described as follows:

Algorithm A2 System EE Maximization

```
Input: $CU$, $UB$, $PL^{CU}$, $PL^{UB}$, $\mu_1$
Output: Matching $\mu_2$
Step 1 Proposing
    Every free $CU_k$ proposes to their favourite $UB_u$ in their preference lists, and removes $UB_u$ from the list.
Step 2 Reallocation
    Each $CU_k$ is accommodated in $UB_u$ by deleting its non-favorite partners in $\mu_2$, to ensure that the occupying slot time does not exceed the available slot time
    All the deleted CUs can be accommodated by other UBs. A matching $\mu_k$ is formed.
    EE increases from matching $\mu_1$ to $\mu_k$.
    $\mu_k$ is stored if all the above three criteria are fulfilled. Step 2 is performed until all free CUs have gone through Step 2.
Step 3 Accepting/rejecting
    The $\mu_k$ that increases the system's EE most is updated; $CU_k$ is set to be served. The rest $\mu_{k'}$ are rejected, and $CU_{k'}$ are rejected and set to be free.
Criterion
    Each CUs is either allocated with a UB or its preference list is empty, this algorithm is terminated with an output $\mu_2$.
    Otherwise, step 1, step 2 and step 3 are performed again.
```

Theorem 4. *Stability of μ_2. In any instance of one-to-many matching, stability is achieved by using A2 in μ_2.*

Proof: We prove this theorem by contradiction and assume that for an instance of one-to-many matching, A2 terminates with an instable matching μ_2, i.e., there exists at least one blocking pair (CU_k, UB_u) or one blocking individual CU_k or UB_u.

If there exists one blocking pair (CU_k, UB_u) in μ_2:

- Case 1: In μ_2, UB_u is unmatched and CU_k is matched with UB'_u. If UB_u is not on the preference list of CU_k, then, CU_k does not have an incentive to match with UB_u; If $pri(CU_k, UB_{u'}) > pri(CU_k, UB_u)$, and CU_k is matched with UB'_u in μ_2, then CU_k does not have an incentive to match with UB_u; If $pri(CU_k, UB_u) > pri(CU_k, UB_{u'})$, then CU_k proposes UB_u before $UB_{u'}$ in A1, or re-matches to UB_u before $UB_{u'}$ in A2. The result is that CU_k matches to $UB_{u'}$, meaning that CU_k is rejected at some stage in A1 or A2. In conclusion, in any situation in which CU_k is matched and UB_u is unmatched, a blocking pair does not exist.
- Case 2: In μ_1, UB_u being unmatched and CU_k unmatched. UB_u is unmatched means that it receives no proposal from CU, including CU_k in both A1 and A2. As both A1 and A2 terminate when every CU is matched or its preference list is empty. UB_u being unmatched means that either its preference list is empty or does not contain UB_u. Then CU_k does not have an incentive to match with UB_u. In conclusion, in any situation in which both CU_k and UB_u are unmatched, a blocking pair does not exist.
- Case 3: In μ_1, UB_u being matched with CU'_k and CU_k unmatched. CU_k is unmatched means that either it has no UB_u in its preference list, or all its proposal have been rejected in both A1, and CU_k can not be matched to any UBs in the reallocation stage inA2. For the former case, CU_k does not have an incentive to match with UB_u. For the latter case, UB_u rejects CU_k because it prefers other proposer(s), and there are not enough spectrum resources in UB_u to serve CU_k. Thus, UB_u does not have incentive to match with CU_k. In conclusion, in any situation in which both CU_k is unmatched and UB_u is matched, a blocking pair does not exist.
- Case 4: In μ_1, UB_u is matched with CU'_k and CU_k with UB'_u. UB_u must be on CU'_ks preference list, and vice versa, otherwise, there is no incentive to form the (CU_k, UB_u) pair. If $pri(CU_k, UB_{u'}) > pri(CU_k, UB_u)$, then, CU_k does not have an incentive to match with UB_u if it is matched with $UB_{u'}$. If $pri(CU_k, UB_u) > pri(CU_k, UB_{u'})$, then, CU_k proposes to UB_u first and is rejected, either because UB_u prefers CU'_k to CU_k, or (UB_u, CU'_k) is formed in the re-allocation stage. For the former, UB_u does not have an incentive to match with CU'_k. For the latter, UB_u does not have sufficient spectrum resource to serve CU_k, otherwise, the (CU_k, UB_u) pair has been formed in μ_2. In conclusion, in any situation in which both CU_k and UB_u are matched, a blocking pair does not exist.

Contradictions, as (CU_k, UB_u) is any pair, thus, we could say that there is no blocking pair in matching μ_1.

If there exists one blocking individual CU_k or UB_u in μ_1: for blocking individual CU_k:

- Case 1: In μ_1, CU_k is matched with UB_u, i.e., UB_u

is on CU_k's preference list, then CU_k does not have an incentive to be unmatched. In conclusion, in any situation in which both CU_k is matched and blocking individual CU_k does not exist.

the proof that blocking individual UB_u does not exist is similar to that blocking individual CU_k does not exist.

In the above proof, blocking pair (CU_k, UB_u), blocking individual CU_k or UB_u can be any pair or individual, thus, we could prove that there is no blocking pair or blocking individual in matching μ_1. ■

Theorem 5. *Praeto optimality of μ_2. In any instance of one-to-many matching, Praeto optimality is achieved by using A2 in μ_2.*

Proof: In stable matching μ_1:

- Case 1: An unmatched CU_k exists, which can be matched to UB_u to increase the achievable EE of both CU_k and UB_u, meaning that (CU_k, UB_u) is the blocking pair of matching μ_1, contracting **Theorem 4**.
- Case 2: An existing a (CU_k exists, UB_u) pair. Obviously, CU_k does not have an incentive to be unmatched; CU_k has the incentive to change partner from UB_u to $UB_{u'}$ to increase its achievable EE, meaning that (UB_u, $UB_{u'}$) is a blocking pair of matching μ_1, contracting **Theorem 4**.

It is impossible to increase the EE of a CU without decreasing that of the remaining CUs. The statement stands for UB, which can be proven similarly as above. ■

Theorem 6. *Complexity of A2 (Convergence of A2). In any instance of many-to-one matching, a matching μ_2 can be obtained by using A2 based on matching μ_1 within $\mathcal{O}(mU(K-m)(U-1))$ iterations, where m is the number of unmatched CUs in μ_1.*

Proof: At every step in A2, each one of m unmatched proposes to favourite UB, such as UB_u, in its current preference list. The maximum number of CUs being matched to UB_u in mu_1 is $(K-m)$. Then, the matched CUs of UB_u will be deleted from mu_1 and re-matched to the rest of UBs in their preference lists. The maximum number of CUs that are deleted is $(K-m)$. For each deleted CU, the maximum number of UBs in its preference list is $(U-1)$. Thus the maximum number of accepting/rejecting decisions made is $(K-m)(U-1)$ for each proposal of an unmatched CU. As there m unmatched CUs, the total number of accepting/rejecting decisions made is $(K-m)(U-1)*mU$. ■

V. NUMERICAL RESULTS AND ANALYSIS

A. Simulation Setting

We perform a Monte Carlo simulation in a circle with a radius of 100m, with CUs randomly and uniformly distributed being served by a SCBS. The throughput requirements of Wi-Fi users and CUs are both random values between the range of [0, TR^W] and [0, TR^C], respectively. We evaluate the performance of the proposed algorithm in the network with the number of CUs. We assume the total number of UB to be 9. We set the slot time T to be 10 μs, and the sub-frame duration t to be 1 μs, which is much smaller than the channel coherence time. For each scenario with a certain network density and traffic load level, simulation is run 10,000 times. CUs are randomly located in the area of interest 100 times, and in each time channel fading is performed 100 times. All other parameters can be referred to in Table. II.

TABLE II
PARAMETERS FOR LTE-U UPLINK EE OPTIMIZATION SIMULATION

Number of CUs	6, 9, 12, 15, 18 and 21
Network Radius	100 m
CU Traffic Level (TR^C)	10, 15, 20, 25, 30, 35 and 40 Mbps
WU Traffic Level (TR^W)	20 Mbps
Unlicensed Spectrum	5 GHz
UB Bandwidth	20 MHz
CU Transmission Power	20 mw
T	10 μ s
t	1 μ s
Packet Size	12800 bits
MAC header	272 bits
PHY header	128 bits
ACK	112 bits + PHY header
Wi-Fi & LAA Bit Rate	50 Mbit/s
$CW_{initial}$	8
Slot Time	9 μs
SIFS	16 μs
DIFS	34 μs

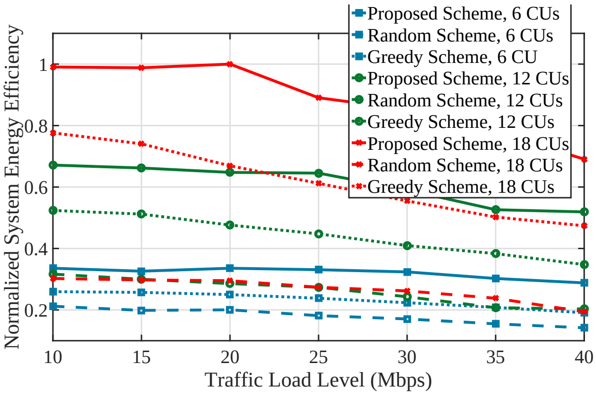

Fig. 3. System Energy Efficiency for Scenarios with Different Number of CUs

B. Numerical Results

1) EE and Fairness Between CUs: We first analyse the system EE obtained by the proposed matching-based scheme in scenarios with a different number of CUs and traffic load level in Fig. 3. Our proposed algorithm outperforms the greedy algorithm and random allocation under both low-density (6 CUs) and high-density networks (18 CUs) with a light traffic load from 10 Mbps per CU and heavy traffic load at 40 Mbps per CU. The system EE improves 30% and 50% obtained by our proposed method as compared with that obtained by the greedy algorithm, under the light and the heavy traffic load scenarios respectively. For the same number of CUs, with the increasing of traffic load per CU, the system EE decreases because more CUs remain unserved in the heavy traffic load scenario, as shown in Fig. 4. This is because more resources are occupied to serve a CU with a high traffic demand, leading to a drop in the number of CUs that can served in the network, i.e., more CUs fail to achieve their throughput requirement.

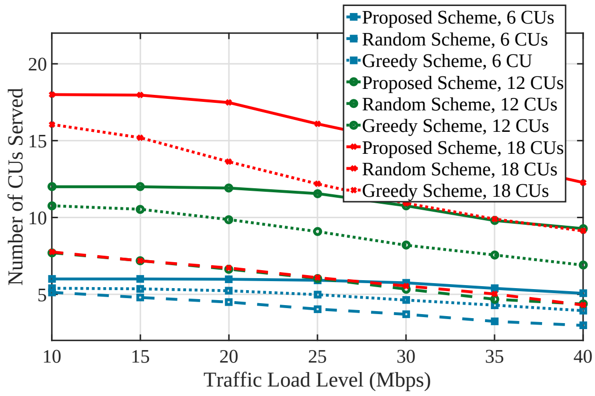

Fig. 4. The Number of CUs Served

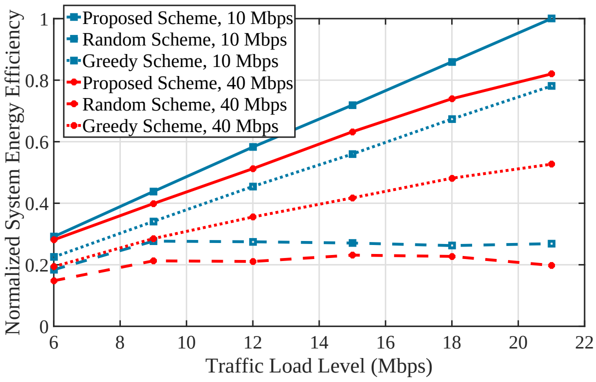

Fig. 5. System Energy Efficiency in Different Traffic Load Level

On the contrary, with the same traffic load level, more CUs tend to be served in the dense scenarios, leading to an increase of system EE as shown in Fig. 5. In dense scenario, more CUs have the chance to meet their throughput requirement, due to many factors, such as the distance between CU and SCBS and channel condition between CU and SCBS. Although the number of CUs served increases with the number of CUs in the network, except for the low traffic demand scenario, the percentage of CUs that have their throughput requirement fulfilled drops, as shown in Fig. 6. In a low traffic demand scenario, where the spectrum resource is sufficient to serve every CU with their required throughput demand, almost 100% of CUs' being served rate is achieved by the proposed algorithm, compared with less than 90% achieved by the greedy algorithm and the even lower served rate when using a random algorithm. In medium and high traffic demand scenario, the percentage of CUs served decreases with the increase of CUs in the network by using any one of the three algorithms. However, the proposed algorithm still outperforms the greedy algorithm and random algorithm by around 35% and 50% 120%, respectively. Thus, we could say that the proposed algorithm works more effectively in CUs' fairness compared with the greedy algorithm or the random allocation scheme.

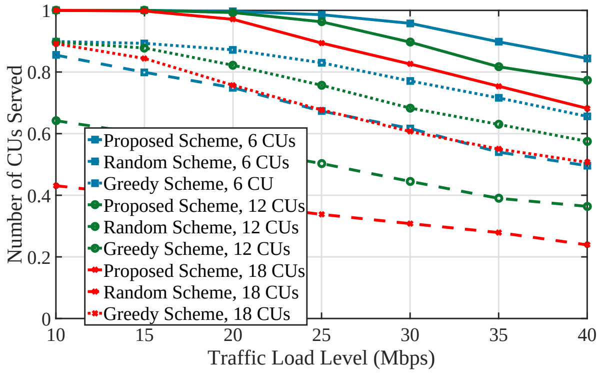

Fig. 6. The Percentage of CUs Served Comparison

2) *Throughput Analysis:* Throughput is another performance matrix for both the system and an individual CU. As shown in Fig. 7, in the 6 CUs scenarios with low traffic demand, three algorithms achieve similar results. This is because the unlicensed spectrum resource is sufficient to serve every CU with their relatively low traffic demands. In low traffic demand, system throughput increases with the number of CUs almost linearly as shown by using the proposed algorithm and the greedy algorithm, because the spectrum resource is still sufficient. The proposed algorithm outperforms the greedy algorithm. However, there is another aspect in heavy traffic load. In the network with 6 CUs, the proposed algorithm achieves 66% more than the greedy algorithm, and more than 100% more than the random scheme. With the increase of the number of CUs in the network, the overall throughput achieved by using the proposed algorithm tends to saturate in heavy traffic load scenarios. This is because the capacity is limited by the available unlicensed spectrum resources.

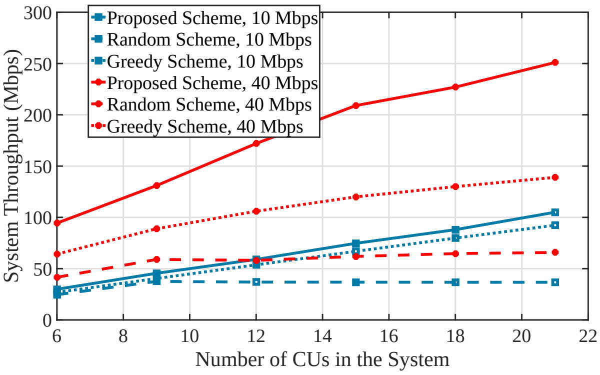

Fig. 7. System Throughput In Different Traffic load Level

3) *Computational Complexity:* The theoretical upper bound of the computation complexity of A1 and A2 have been given in **Theorem 3**, and **Theorem 6**. Here we show the actual

computation complexity of the proposed algorithm in typical traffic load scenarios in Fig. 8.

There are positive correlations between the complexity and network density at the same traffic load level. Specifically, at the lowest traffic load (10 Mbps), complexity is slightly more than the number of CUs in the network. This means that almost all the CUs' first proposal are accepted, due to the low traffic demand of each CU. In a low traffic case, most CUs are matched by using $A1$; $A2$ is seldom performed. The complexity increases with the traffic load level from 10 to 30 Mbps. This is because with the increase of traffic load level, increasing CUs are unmatched in μ_1 by using $A1$; the number of iterations that $A2$ performs is increasing. The complexity of an iteration in $A2$ ($\mathcal{O}((K-m)(U-1))$) is much larger than that in $A1$ ($\mathcal{O}(U)$), leading to an increase of complexity. At an even higher traffic load level, the complexity begins to drop. At this stage, the number of UBs in a CU's preference lists is much smaller than that in a medium traffic load level. The complexity of obtaining matching μ_1 is much smaller. Although the number of unmatched CUs rises in the scenario with the same network density, elements in their preference lists are much smaller, the complexity in an iteration drops significantly, leading to the decrease of computational complexity at a high traffic load level.

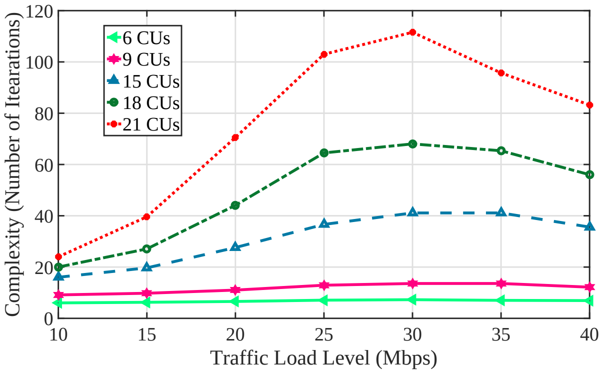

Fig. 8. Computational Complexity in Different Scenario

VI. CONCLUSION

In this work, we have studied the uplink resource allocation problem in a LTE-U and Wi-Fi coexistence scenario to maximize each CU's EE. We formulated the problem as a multi-objective optimization, and transformed it into a single-objective optimization by using the weighted-sum method. We proposed a semi-distributed 2-step matching with partial information based algorithm to solve the problem. Compared with the greedy algorithm based resource allocation scheme, our proposed scheme achieves improvements of up to 50% in terms of EE and up to 66% in terms of throughput. Furthermore, we have analysed the computational complexity of the proposed algorithm theoretically and by simulations, thereby showing the complexity is reasonable for real-world deployment.

In the future, work will be extended into the heterogeneous LTE-U networks, where hyper-dense deployment of LTE-U cells may exist. We will also consider a comprehensive optimized resource allocation scheme for LTE-U taking into account that CU can choose between licensed and unlicensed bands. In such scenarios, a multi-side matching model should be considered, which poses new challenges in achieving the solutions.

ACKNOWLEDGMENT

This paper acknowledges the support of the MOST of China for the ”Small Cell and Heterogeneous Network Planning and Deployment” project under grant No. 2015DFE12820. This work was partly funded by the European Unions Horizon 2020 Research and Innovation Programme under the grant agreement No 645705.

REFERENCES

[1] A. Bleicher, “A surge in small cells [2013 tech to watch],” *IEEE Spectrum*, vol. 50, no. 1, pp. 38–39, 2013.

[2] B. Chen, J. Chen, Y. Gao, and J. Zhang, “Coexistence of LTE-LAA and Wi-Fi on 5 GHz with corresponding deployment scenarios: A survey,” *IEEE Communications Surveys & Tutorials*, vol. 19, no. 1, pp. 7–32, 2017.

[3] M. Wang, J. Zhang, B. Ren, W. Yang, J. Zou, M. Hua, and X. You, “The evolution of LTE physical layer control channels,” *IEEE Communications Surveys & Tutorials*, vol. 18, no. 2, pp. 1336–1354, 2016.

[4] Y. L. Lee, T. C. Chuah, J. Loo, and A. Vinel, “Recent advances in radio resource management for heterogeneous LTE/LTE-A networks,” *IEEE Communications Surveys & Tutorials*, vol. 16, no. 4, pp. 2142–2180, 2014.

[5] G. Ku and J. M. Walsh, “Resource allocation and link adaptation in LTE and LTE advanced: A tutorial,” *IEEE Communications Surveys & Tutorials*, vol. 17, no. 3, pp. 1605–1633, 2015.

[6] Y. Wu, W. Guo, H. Yuan, L. Li, S. Wang, X. Chu, and J. Zhang, “Device-to-device meets LTE-unlicensed,” *IEEE Communications Magazine*, vol. 54, no. 5, pp. 154–159, May 2016.

[7] A. Babaei, J. Andreoli-Fang, Y. Pang, and B. Hamzeh, “On the impact of LTE-U on Wi-Fi performance,” *International Journal of Wireless Information Networks*, vol. 22, no. 4, pp. 336–344, 2015.

[8] N. Rupasinghe and İ. Güvenç, “Licensed-assisted access for WiFi-LTE coexistence in the unlicensed spectrum,” in *Globecom Workshops (GC Wkshps), 2014*. IEEE, 2014, pp. 894–899.

[9] E. Alcatel-Lucent and S. Qualcomm, “Verizon,LTE-U Technical Report Coexistence Study for LTE-U SDL V1. 0, LTE-U Forum,” Tech. Rep., Feb. 2015. Accessed on 10/06, Tech. Rep., 2016.

[10] H. Zhang, X. Chu, W. Guo, and S. Wang, “Coexistence of wi-fi and heterogeneous small cell networks sharing unlicensed spectrum,” *IEEE Communications Magazine*, vol. 53, no. 3, pp. 158–164, 2015.

[11] C. Chen, R. Ratasuk, and A. Ghosh, “Downlink performance analysis of LTE and WiFi coexistence in unlicensed bands with a simple listen-before-talk scheme,” in *Vehicular Technology Conference (VTC Spring), 2015 IEEE 81st*. IEEE, 2015, pp. 1–5.

[12] *ETSI EN 301 893 V1.7.1*, ETSI Std., June 2012.

[13] A. Al-Dulaimi, S. Al-Rubaye, Q. Ni, and E. Sousa, “5G communications race: Pursuit of more capacity triggers LTE in unlicensed band,” *IEEE vehicular technology magazine*, vol. 10, no. 1, pp. 43–51, 2015.

[14] M. Chiang *et al.*, “Geometric programming for communication systems,” *Foundations and Trends® in Communications and Information Theory*, vol. 2, no. 1–2, pp. 1–154, 2005.

[15] Q. Chen, G. Yu, H. Shan, A. Maaref, G. Y. Li, and A. Huang, “Cellular meets WiFi: Traffic offloading or resource sharing?” *IEEE Transactions on Wireless Communications*, vol. 15, no. 5, pp. 3354–3367, 2016.

[16] H. Ko, J. Lee, and S. Pack, “A fair listen-before-talk algorithm for coexistence of LTE-U and WLAN,” *IEEE Transactions on Vehicular Technology*, vol. 65, no. 12, pp. 10 116–10 120, 2016.

[17] Y. Gu, Y. Zhang, L. X. Cai, M. Pan, L. Song, and Z. Han, “Exploiting student-project allocation matching for spectrum sharing in LTE-unlicensed,” in *Global Communications Conference (GLOBECOM), 2015 IEEE*. IEEE, 2015, pp. 1–6.

[18] X. C. Y. Gao, B Chen and J. Zhang, “Resource Allocation in LTE-LAA and WiFi Coexistence: A Joint Contention Window Optimization Scheme,” in *Globecom (GC), 2017*. IEEE, 2017.

[19] K. Hamidouche, W. Saad, and M. Debbah, “Multi-Games for LTE and WiFi Coexistence over Unlicensed Channels,” in *International Conference on Network Games, Control, and Optimization*. Springer, 2016, pp. 123–133.

[20] C. Cano and D. J. Leith, “Coexistence of WiFi and LTE in unlicensed bands: A proportional fair allocation scheme,” in *Communication Workshop (ICCW), 2015 IEEE International Conference on*. IEEE, 2015, pp. 2288–2293.

[21] S. Sagari, S. Baysting, D. Saha, I. Seskar, W. Trappe, and D. Raychaudhuri, “Coordinated dynamic spectrum management of LTE-U and Wi-Fi networks,” in *Dynamic Spectrum Access Networks (DySPAN), 2015 IEEE International Symposium on*. IEEE, 2015, pp. 209–220.

[22] Q. Ni and C. C. Zarakovitis, “Nash bargaining game theoretic scheduling for joint channel and power allocation in cognitive radio systems,” *IEEE Journal on selected areas in Communications*, vol. 30, no. 1, pp. 70–81, 2012.

[23] Q. Chen, G. Yu, and Z. Ding, “Optimizing unlicensed spectrum sharing for LTE-U and WiFi network coexistence,” *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 10, pp. 2562–2574, 2016.

[24] M. Ali, S. Qaisar, M. Naeem, J. J. Rodrigues, and F. Qamar, “Resource allocation for licensed and unlicensed spectrum in 5g heterogeneous networks,” *Transactions on Emerging Telecommunications Technologies*, p. e3299.

[25] S. Nielsen and A. Toskala, “LTE in unlicensed spectrum: European regulation and co-existence considerations,” in *3GPP workshop on LTE in unlicensed spectrum*, 2014.

[26] A. Garnaev, S. Sagari, and W. Trappe, “Fair channel sharing by Wi-Fi and LTE-U networks with equal priority,” in *International Conference on Cognitive Radio Oriented Wireless Networks*. Springer, 2016, pp. 91–103.

[27] C. Yang, J. Li, Q. Ni, A. Anpalagan, and M. Guizani, “Interference-aware energy efficiency maximization in 5G ultra-dense networks,” *IEEE Transactions on Communications*, vol. 65, no. 2, pp. 728–739, 2017.

[28] D. Feng, C. Jiang, G. Lim, L. J. Cimini, G. Feng, and G. Y. Li, “A survey of energy-efficient wireless communications,” *IEEE Communications Surveys & Tutorials*, vol. 15, no. 1, pp. 167–178, 2013.

[29] G. Y. Li, Z. Xu, C. Xiong, C. Yang, S. Zhang, Y. Chen, and S. Xu, “Energy-efficient wireless communications: tutorial, survey, and open issues,” *IEEE Wireless Communications*, vol. 18, no. 6, 2011.

[30] Y. Gu, W. Saad, M. Bennis, M. Debbah, and Z. Han, “Matching theory for future wireless networks: fundamentals and applications,” *IEEE Communications Magazine*, vol. 53, no. 5, pp. 52–59, 2015.

[31] B. Di, S. Bayat, L. Song, Y. Li, and Z. Han, “Joint user pairing, subchannel, and power allocation in full-duplex multi-user OFDMA networks,” *IEEE Transactions on Wireless Communications*, vol. 15, no. 12, pp. 8260–8272, 2016.

[32] S. Sekander, H. Tabassum, and E. Hossain, “Decoupled uplink-downlink user association in multi-tier full-duplex cellular networks: A two-sided matching game,” *IEEE Transactions on Mobile Computing*, vol. 16, no. 10, pp. 2778–2791, 2017.

[33] J. Zhao, Y. Liu, K. K. Chai, Y. Chen, and M. Elkashlan, “Many-to-Many Matching With Externalities for Device-to-Device Communications,” *IEEE Wireless Communications Letters*, vol. 6, no. 1, pp. 138–141, 2017.

[34] Y. Gu, C. Jiang, L. X. Cai, M. Pan, L. Song, and Z. Han, “Dynamic Path To Stability in LTE-Unlicensed with User Mobility: A Matching Framework,” *IEEE Transactions on Wireless Communications*, 2017.

[35] G. Bianchi, “Performance analysis of the ieee 802.11 distributed coordination function,” *IEEE Journal on selected areas in communications*, vol. 18, no. 3, pp. 535–547, 2000.

[36] S. Ruzika and M. M. Wiecek, “Approximation methods in multiobjective programming,” *Journal of optimization theory and applications*, vol. 126, no. 3, pp. 473–501, 2005.

[37] D. F. Manlove, *Algorithmics of matching under preferences*. World Scientific, 2013, vol. 2.

[38] K. Iwama and S. Miyazaki, “A survey of the stable marriage problem and its variants,” in *Informatics Education and Research for Knowledge-Circulating Society, 2008. ICKS 2008. International Conference on*. IEEE, 2008, pp. 131–136.

[39] A. Shrivastava and C. P. Rangan, “Stable marriage problem with ties and incomplete bounded length preference list under social stability,” *arXiv preprint arXiv:1601.03523*, 2016.