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Dynamic Path To Stability in LTE-Unlicensed with User Mobility: A Matching Framework

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***Abstract*—LTE-Unlicensed, has recently captured intensive attention from both academic and industrial fields. By integrating the unlicensed spectrum with the licensed spectrum, using carrier aggregation, LTE-Unlicensed users can experience enhanced transmission, while maintaining the seamless mobility management and predictable performance. However, due to different transmission regulations, the coordination between LTE and Wi-Fi systems requires careful design. Especially, it's important to understand how to guarantee the transmission quality for LTE users and reduce Wi-Fi users' performance degradation, under the impact of the co-channel interference. In other words, how can we solve the unlicensed resource allocation problem under both LTE and Wi-Fi transmission requirements? In this work, we propose a matching theory framework to tackle this problem. Specifically, the coexistence between LTE and Wi-Fi systems, i.e., the interaction between LTE and Wi-Fi users, is modeled as the stable marriage (SM) game. The coexistence constraints are interpreted as the preference lists. Two semi-distributed solutions, namely the Gale-Shapley (GS) and the Random Path to Stability (RPTS) algorithms are proposed. What's more, to address the external effect in matching, the Inter-Chanel Cooperation algorithm is introduced. Last but not least, the resource allocation problem is studied with network dynamics, and the proposed mechanisms are evaluated under two typical user mobility models.**

***Index Terms*—LTE-Unlicensed, user mobility, stable marriage problem, random path to stability, matching theory**

I. Introduction

The ever increasing mobile broadband traffic load leads to a pressing need for additional spectral resources for the future 5G networks. To meet this demand, an intuitive idea is to exploit more licensed spectrum, which ensures reliable and predictable performance. However, it is not quite possible that sufficient additional licensed spectrum can be available in the near future. A growing interest in exploiting the unlicensed spectrum to boost the network capacity has recently arisen. Some cellular network operators (CNOs) have deployed Wi-Fi access points (APs) to offload cellular traffic to the unlicensed spectrum. However, such efforts are limited by some disadvantages such as extra cost due to the investment on backhaul and core networks, degradation of the Wi-Fi performance, and lack of good coordination between cellular and Wi-Fi systems. Another way to augment the LTE capacity to meet the traffic demands is to integrate the unlicensed carriers into the LTE system to enhance transmission rate using the carrier aggregation (CA) technology. The CA technology provides the option of aggregating two or more component carriers into a combined virtual bandwidth for enhanced transmission [1]. By aggregating the unlicensed spectrum into cellular networks with CA, the capacity of the LTE network can be boosted, while maintaining the seamless mobility and predictable performance. This technology is commonly referred to as the LTE-Unlicensed [2].

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A. LTE-Unlicensed Coexistence Issue

Recent studies have highlighted that LTE technology has significant performance gains over Wi-Fi when operating in the unlicensed band [3]. The main advantages for LTE-Unlicensed over Wi-Fi on the unlicensed spectrum include better link performance, medium access control, mobility management, and excellent coverage. These benefits have made LTE-Unlicensed a promising technology. Due to the low power and high frequency transmission regulations imposed by Federal Communications Commission (FCC) on the unlicensed spectrum, small cell (SC) deployment is an ideal implementation scenario for the LTE-Unlicensed. It is shown in [4] that LTE-Unlicensed has a great potential in the ultra dense cloud SC deployment, which combines advantages of the cloud radio access network and ultra dense SCs. However, LTE-Unlicensed is still in its infancy, and thus calls for great effort and careful design before the it can meet the requirements and regulations of both licensed and unlicensed transmissions. More specifically, how can we guarantee a fair coexistence of the newly joined cellular users (CUs) and the existing unlicensed users (UUs) on the unlicensed band? For traditional Wi-Fi transmission, which is collision avoidance based, UUs may back off to the co-channel LTE-Unlicensed users if the interference level is above the energy detection threshold (e.g., -62dBm over 20MHz) [3]. Thus without proper

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coexistence mechanisms, LTE-Unlicensed transmissions can cause considerable interference on Wi-Fi transmissions. On the other hand, the interference from the co-channel Wi-Fi users may also degrade the LTE-Unlicensed devices' performance, leading to the failure of meeting the quality of service (QoS) requirements for cellular transmissions. In addition, with limited unlicensed bands, LTE-Unlicensed users (among multiple CNOs) need to compete with each other. Thus, there may exist inter-operator interference. To summarize, such unplanned and unmanaged deployment can result in excessive interference to both Wi-Fi users and LTE-Unlicensed users. Therefore, it is critical to design a coexistence mechanism to avoid such co-channel interference and guarantee the harmonious coexistence of Wi-Fi and LTE systems [5].

The exiting projects on LTE-Unlicensed come in multiple forms, Licensed Assisted Access (LAA), LTE-U and MuLTE-fire [6]. The LTE-U targets on mobile operator deployments in markets without the listen-before-talk (LBT) regulation on the unlicensed spectrum, while in markets with LBT regulation, LAA is specified. For both LTE-U and LAA, the signaling and control messages are sent through the reliable licensed anchor, and the unlicensed link is used only for data. The MuLTEfire broadens the LTE ecosystem to new deployment opportunities by operating solely in the unlicensed spectrum without a licensed anchor channel. For markets without LBT regulations, such as the United States and China, the coexistence mechanism can be realized through careful software design. It allows for fast-time-to-market launch. On the other hand, for markets with LBT regulation, a number of modifications are needed to meet the channel occupancy requirements on the uplink (UL) and downlink (DL) transmissions in the unlicensed band and even modifications in the radio air interface [6].

A fair coexistence is always evaluated from both the LTE-Unlicensed and Wi-Fi users' point of view, and thus the coexisting interference can be majorly catagerized into three types: (1) the interference that CUs bring to the existing UUs; (2) the interference that the existing UUs bring to CUs; (3) the interference between multiple CUs who are reusing the same unlicensed band. Therefore, to satisfy these coexisting constraints, certain transmission restrictions should be imposed on both LTE and Wi-Fi systems. Some methods have been proposed to deal with the coexistence issues, for example the Channel Selection mechanism, Carrier-Sensing Adaptive Transmission (CSAT) and Opportunistic SDL [6]. The Channel Selection method enables the SCs to choose the cleanest channel based on the Wi-Fi and LTE measurements. When no clean channel is available, the CSAT algorithm can be used to apply adaptive TDM transmission based on the long-term carrier sensing of co-channel Wi-Fi activities. The SDL method allows to turn off the carrier aggregation when the SC is lightly loaded to avoid interference to Wi-Fi and transmission overheads. It is pointed out that, for most Wi-Fi and LTE-Unlicensed SC deployments, Channel Selection is usually sufficient to meet the coexistence requirements [6]. In the case that one unlicensed band is the best choice for more than one CU, instead of allocating all such CUs to this unlicensed band, some CUs can be allocated to their second-best or third-best choices for more efficient network utilization. Thus, it becomes a critical issue, from the LTE-Unlicensed SCs' perspective, that how to most efficiently allocate the unlicensed bands to multiple CUs so that the unlicensed resources can achieve the highest utilization while both cellular and Wi-Fi users' performances can meet their requirements/regulations.

B. Matching Theory for LTE-Unlicensed

To find a proper solution for this unlicensed resource allocation problem between the CUs and coexisting UUs, we start by studying the features of the resource allocation problem and some existing solution methods. The future 5G mobile networks are expected to be characterized with features such as higher data rates, reduced end-to-end latency, better network coverage and so on. The heterogeneous characteristics exhibited by mobile users and the network density are the two major challenges that face the 5G design. Current architectures for mobile and cellular networks are highly centralized. The advantage of the centralized approach resides in its optimality, however with the gigantic information to be collected by the centralized agent (e.g., eNBs) and the extremely high computation complexity, the resulting service latency to the end users can be unsatisfying. In addition, considering the highly dynamic network environment, including the network topology change and channel condition varying, distributive network resource management is considered as a more efficient approach. More specifically, in the LTE-Unlicensed context, with eNBs in control of the resource allocation, we can formulate the unlicensed resource allocation as a centralized optimization with interference constraints. As discussed previously, the network density, the user heterogeneity, the require for global information, as well as the mobility management, may result in high computation overhead and complexity, which make the centralized approach less efficient. As a popular mathematical tool, game theory is often used as an alternative approach to solve these problems in a distributed manner. We can model the resource allocation problem as the interactions between players under certain rules. However, game theory also has its limitations, for example that each player requires the knowledge of other players' actions in many cases, which restricts its distributive implementation. In addition, specific utility functions are always required for players, which is hard to realize in some practical applications.

Matching game, as a Nobel-prize winning framework, can overcome some limitations of game theory and centralized optimization. It can model the competition and negotiation between the distinct user sets of LTE and Wi-Fi, and solve the problem in a semi-distributive way. We claim it as semi-distributive w.r.t. the fact that many operations in the matching algorithms are implemented distributively, including the information collection, preference list set up, local reject/accept decision making and so on, while certain operations may require global information from a centralized agent, such as the detection of a blocking pair. Different from the static resource allocation that has been studied [7] [8], which is a one-time allocation, the dynamic case is not a simple repeating of the static allocation over time. In this work, we propose

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a matching-based framework to tackle the dynamic LTE-Unlicensed resource allocation problem, which explores the relations between the resource allocations of adjacent times. The major contributions are summarized as follows.

- We have summarized the coexistence issues of LTE-Unlicensed into three categories. To solve such issues we have modeled the interactions between CUs and UUs as an interactive matching game: the stable marriage (SM) problem. The coexistence constraints are well interpreted through the set up of CUs' and UUs' preference lists.
- We have introduced two semi-distributed solutions: the Gale-Shapley (GS) algorithm and Random Path to Stability (RPTS) algorithm to tackle the resource allocations in LTE-Unlicensed dynamically. Both mechanisms ensure network stability, while achieving relatively low computation complexity compared with the centralized optimization. Specifically, the proposed RPTS algorithm, which makes use of the relations between two time-adjacent matchings, further reduces complexity compared with GS, and is more suitable for dynamic networks.
- The external effect that occurs in many wireless resource allocation problems, which refers to instability caused by the inter-dependence of the matching players' preference lists, is addressed by the proposed Inter-Channel Cooperation (ICC) mechanism. The ICC procedure not only re-stabilize the system but also further improves network throughput.
- We evaluate the adaptability and robustness of the GS+ICC and RPTS+ICC mechanisms under two user mobility models: the Random Waypoint model, and the HotSpot model. The computation complexity and system optimality analysis are performed theoretically and also validated through simulations.

The rest of the paper is organized as follows. Related works are discussed in Section II. The system model of the dynamic resource allocation in LTE-Unlicensed is provided in Section III. Then, the problem formulation and centralized solution are presented in Section IV. Due to the NP-hardness of the centralized solution, the semi-distributive matching approaches are introduced in Section V. Two matching mechanisms are implemented in the time-independent way and the time-dependent way, respectively. Both theoretical and numerical analysis are provided in Section VI to evaluate the proposed mechanisms. Finally, conclusion remarks are drawn in Section VII.

II. Related Work

The performance evaluation of LTE-Unlicensed has been studied in some recent studies. For example, [9] presents a system performance analysis of the LTE and Wireless Local Area Networks (WLAN) sharing the unlicensed resource using a simple fractional bandwidth sharing mechanism. The simulation results show that the coexistence has a negative impact on the WLAN system performance if without restrictions on the LTE transmission, but the severity of the impact can be controlled by restricting the LTE activities. The results also suggest the silent time of WLAN, when the medium is idle due to the WLAN users backing off, can be exploited by LTE users such that WLAN performance would not necessarily degrade but the total system throughput increases. Similar evaluations are done in [10], which again observes about 70% to 100% performance degradation of Wi-Fi users if there is no inter-system coordination.

Efforts have been devoted to tackle the coexistence issues in the LTE-Unlicensed. To alleviate the coexistence interference between LTE and Wi-Fi systems, some techniques have been proposed, such as channel selection and transmission power control, blank subframe and so on [11]. An intuitive way to prevent LTE/Wi-Fi user from accessing the channel at the same time is: blank subframe, the idea of which is similar to the LTE almost blank subframe technique proposed in 3GPP Rel. 10. By silencing some of the subframes in the LTE UL/DL transmission, Wi-Fi users can access the channel during the blank subframe of LTE to increase throughput [12]. A similar idea is proposed in [13]. Alternatively, LTE users can use transmission power control to enable the LTE/Wi-Fi coexistence [14]. By measuring the interference at the LTE eNBs, LTE users estimate the presence and proximity of Wi-Fi users, and adjust their transmission power to avoid too strong interference to Wi-Fi. The idea of either blank subframe or power control enables the coexistence of LTE/Wi-Fi, however it more or less affects the transmission quality/throughput of the LTE users. Another effective enabler is the channel selection technique for both Wi-Fi and LTE users [11]. For example, some Wi-Fi APs implement the least congested channel search (LCCS) to find the least congested channel. Meanwhile, except for the fixed bandwidth channel, adaptive bandwidth channel allocation can also be defined and utilized in the LTE-Unlicensed environment.

There are some existing works on the resource allocation problem in the LTE-Unlicensed. For example, in [15], a joint user association and unlicensed resource allocation problem is proposed, and the performance is measured by the average packet sojourn time. This work is solved by a centralized optimization approach. Some other works have been proposed by using the cooperative/noncooperative games. For example in [7], a coordinated hierarchical game is proposed for modeling a multi-operator spectrum sharing in LTE-Unlicensed, where a Kalai-Smorodinsky bargaining game is modeled among operators and a Stackelberg game is modeled between operators and users. By assuming the operators as the leaders, and the CUs as the followers, the interactions between the operators and the CUs are modeled as the negotiations between the leaders and followers. The operators offer CUs certain unlicensed resources, and in exchange charge them certain monetary payment. Here, the operators are responsible for and can represent the benefit of the unlicensed resources or UUs. Thus, the price is set based on the interference that CUs cause to the coexisting UUs. After the operators set the prices, the CUs will fine tune their transmission powers to optimize their own utilities according to the prices offered by the operators. Finally, the network equilibrium can be achieved through the negotiation (by varying the transmission power and price) between the CUs and operators (representing the UUs). However, the key idea of using matching in the

LTE-Unlicensed is to find proper/stable UU partners for CUs, while no transmission parameter will be changed. Although the players in both the Stackelberg game and matching are the CUs and UUs, the game rules are designed differently. In the Stackelberg game, players negotiate with fixed players/partners by finding the trade-off between monetary payment and transmission parameters, while in the matching, players try to be matched with stable/proper players/partners with fixed transmission parameters. An interesting idea of leveraging the LTE-Unlicensed to transfer Wi-Fi users to the LTE-Unlicensed system, while offering them the unlicensed bands for compensation, is proposed in [16]. They developed a Nash bargaining solution (NBS) method to find the close-form expression for the unlicensed time slot allocation and the optimal number of transferred users. A matching based approach that addresses the LTE-Unlicensed coexistence issue has been discussed in [8]. The student-project allocation (SPA) matching game was utilized to model the interactions between LTE and Wi-Fi users. The interference between LTE and Wi-Fi users can be avoided by generating the preference lists for both types of users, while the interferences among co-channel LTE users are avoided by utilizing the TDMA method. However, this work only considers the static resource allocation, and the dynamic resource management issue in LTE-Unlicensed remains unexplored. A dynamic sharing problem among multiple operators in the unlicensed spectrum with time-varying traffic has been proposed in [17]. By modeling it as the repeated game, operators change the power spectral density (PSD) to optimize utilities in different time slots. Again, this dynamic game only considers the Wi-Fi transmission regulation, but fails to consider the interference from Wi-Fi system to LTE system. Besides, only DL transmission is discussed in this work.

Except the game-based and matching-based analytical frameworks, there are also other models, such as the Markov chain model, that are adopted for the LTE Unlicensed resource allocations. For example, in [18], two separate Markov chain models are established for both LAA and Wi-Fi system in the unlicensed band. By calculating the downlink throughput for both systems using the Markov chain model, the results indicate that the LBT scheme is very effective in the LAA and Wi-Fi coexisting scenarios. Another work [19], based on the statistical measuring and estimation, is proposed for LTE-U. It considers the duty-cycle mechanism for LTE-U to access the unlicensed spectrum. Using the channel monitoring, the eNBs can dynamically adapt the probability to access the unlicensed channel and the transmission duration. By taking into account the actual behavior of the Wi-Fi network, the LTE-U can achieve a proportional fair coexistence with Wi-Fi.

The above mentioned work and other existing work on LTE-Unlicensed either addresses only part of the coexistence issue, or does not consider the network dynamic management. To the best of our knowledge, our work is the first that addresses a dynamic coexistence management problem in the LTE-Unlicensed, with joint consideration of different types of coexisting interference.

III. System Model

We consider a single carrier cellular network consisting of CUs $\mathcal{CU} = \{cu_1, ..., cu_i, ..., cu_N\}$ subscribed to one CNO as illustrated in Fig. 1. Each CU is served by its local eNB $\mathcal{BS} = \{bs_1, ..., bs_b, ..., bs_{B_1}\}$ with the allocated licensed spectrum. B_1 is the number of total eNBs. Due to the time varying traffic flow, some transmission requests can not be satisfied by the currently allocated licensed subband. We assume a set of such CUs travel around in the network with certain mobility patterns. Wherever CUs are located, they search for nearby UUs, and seek to share their unlicensed spectrum using the CA technique for supplemental downlink (SDL) transmission. We denote the set of UUs as $\mathcal{UU} = \{uu_1, ..., uu_j, ..., uu_M\}$, and each UU is allocated with a specific unlicensed subband denoted as $\mathcal{F} = \{f_1, ..., f_j, ..., f_K\}$ for transmission. Typically, each unlicensed band is shared by multiple UUs based on the CSMA/CA regulation. All the pathless gains are independent of the unlicensed subbands, and fast fading is not considered in this work. All the unlicensed subbands use the same carrier frequency. To simplify the representation, we assume that $uu_j, uu_j \in \mathcal{UU}$ is assigned with the unlicensed band $f_k, f_k \in \mathcal{F}$. Each UU is served by its local Wi-Fi AP, denoted as $\mathcal{AP} = \{ap_1, ..., ap_j, ..., ap_{B_2}\}$, for transmitting/receiving data, where B_2 is the number of Wi-Fi APs.

The pre-assigned licensed bands of CUs will be the primary carrier and will be aggregated with the shared unlicensed bands to enhance transmission. To access a clean unlicensed channel, CUs need to have the channel sensing phase before joining any unlicensed channel, and this channel sensing shall be repeated each time CUs joins a new unlicensed channel. During the channel sensing, CUs can detect the the transmission energy on the target unlicensed channel and decide if this channel is clean or not by comparing with a threshold. The CUs then communicate with its local eNBs, who assist the CUs in accessing the unlicensed bands, through control signal exchanges using the pre-assigned licensed bands. On the other hand, to model the interference incurred at UUs from the sharing CUs, the locations of UUs and the Wi-Fi medium utilization (MU) estimation should be performed. The Wi-Fi MU monitoring is done by the Wi-Fi APs through network listening, where all the LTE-Unlicensed CUs are required to turn off the unlicensed spectrum sharing in this period. The Wi-Fi network listening decodes the preamble of any WiFi packet detected during this time and records its corresponding received signal strength indicator (RSSI), duration in μs(or NAV), modulation, coding scheme and source/destination address [20]. With the above estimated information of the unlicensed bands and the existing UUs, the Wi-Fi APs will share with the LTE-Unlicensed eNBs so that this information can be further shared with the CUs to select the proper partner UUs. To the best of our knowledge, there's no existing standard specifying how many unlicensed bands that each CU should use for aggregation in LTE-Unlicensed, besides SDL is only considered as an enhancement to LTE transmission without any certain improvement guaranteed. Thus, without loss of generality, we assume in this work, that each CU will be matched to at most one UU, i.e., one

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unlicensed band. On the other hand, each unlicensed band can accommodate multiple CUs, depending on the number of its existing UUs.

As discussed in Section I, the coexistence issues are categorized as follows: (1) the interference that CUs bring to the existing UUs; (2) the interference that the existing UUs bring to CUs; (3) The interference between multiple CUs who are reusing the same unlicensed band. We elaborate them one by one into the following constraints:

- It is well known that in Wi-Fi transmission, the UUs adopt the CSMA/CA mechanism for coexistence, which is different from the way that LTE system operates, who directly uses the spectrum without sensing. Thus, it is required that CUs should keep their interference incurred at the UUs to be sufficiently small, such that the channel is treated as "idle" by UUs. To achieve this requirement, we set the threshold of the any CU's interference as the energy level of UU's noise, denoted as σ_{noise}.
- On the other hand, not all unlicensed bands are clean enough for CUs to use. The existing UUs on some channels cause high interference that greatly reduces the transmission quality rather than enhancing the transmission. Thus, by restricting the signal to interference plus noise ratio (SINR) for cu_i to be higher than the minimum requirement Γ_i^{min} when choosing sharing UUs, we can guarantee CUs' QoS requirements.
- The inter-CU interference can be avoided by the management of eNBs. We assume the eNBs adopt TDMA for CUs who are sharing the same unlicensed bands, and each sharing CU is allocated an equal share of time. As more CUs are assigned to the same unlicensed band, each CU gets a smaller share of the resource. Thus, it might happen that, after assigned to some unlicensed channel, some CU may prefer to switch to another channel which has less CUs assigned. To avoid such situation, we design the ICC strategy to avoid the system-wide massive switching. The detailed mechanism will be discussed in Section V-B2.

IV. Problem Formulation

There are majorly two factors that may cause network dynamics, one is the user mobility, and the other the channel fading. To model the network dynamics, which include the change of propagation gain, interference, and so on, we divide the simulation period $[0, T]$ into identical time slots ΔT. The slot duration ΔT can be set according to specific applications. To precisely model the dynamic network due to user mobility, we can set ΔT to be sufficiently small that during each time slot $(t, t+1), \forall t \in \{1, ..., t, ..., T\}$, the user distribution and channel conditions can be treated as static. In other words, we assume that the resource allocation only happens at the beginning of each time slot. Thus, the formulation of our dynamic resource allocation problem will be built based on each specific time slot $(t, t+1)$.

In order to pursuit higher spectrum efficiency, we allow multiple CUs to share the same unlicensed channel as long as the incurred coexisting interference is acceptable for each co-channel CU and UU. Each CU is only allowed to be allocated to one unlicensed channel. In other words, it is a many-to-one matching between CUs and the unlicensed bands (i.e., UUs). To model the dynamic resource allocation problem between CUs and UUs, we adopt a binary matrix for each time slot, denoted as $\rho(t) = \{\rho_{i,j} | cu_i \in \mathcal{CU}, uu_j \in \mathcal{UU}\}$. $\rho_{i,j}(t)$ is a binary value equal to 1 or 0 indicating if cu_i is or is not assigned with uu_j (i.e., subband f_j) at time t. To dynamically maximize the social welfare, we endeavor to find the allocation matrix $\rho(t)$ sequentially at each time that can achieve the highest overall performance of CUs and UUs.

A. CUs' Performance

In this work, we assume that LTE-Unlicensed for CUs' SDL transmission. Thus, cu_i is the receiver and its local eNB bs_b is the transmitter. The interference from from the coexisting UU is also incurred on the receiver cu_i. Thus, The received SINR at bs_b when sharing f_j with uu_j at time t, used to measure the performance cu_i, is represented as follows:

$$\Gamma_{i,j}(t) = \frac{\rho_{i,j}(t) P_{b,i}(t) g_{b,i}(t)}{\sigma_N^l + P_{j,i}(t) h_{j,i}(t)}, \tag{1}$$

where $P_{b,i}(t)$ and $g_{b,i}(t)$ are the transmission power and channel gain from bs_b to cu_i at time t, respectively. $P_{j,i}(t)$ and $h_{j,i}(t)$ represent the transmission power and channel gain from uu_j to cu_i, respectively. σ_N^l is the licensed channel noise.

B. UUs' Performance

On the other hand, UUs will be interfered by the spectrum sharing from CUs, although the interference is controlled to be small. In the case that f_j is utilized by cu_i for UL transmission, uu_j is interfered by the transmitter cu_i's power. Thus, the interference of uu_j from cu_i at time t is denoted as follows:

$$\text{Intf}_{i,j}^{UL}(t) = P_{i,j}(t) h_{i,j}(t), \tag{2}$$

where $P_{i,j}(t)$ and $h_{i,j}(t)$ represent the transmission power and channel gain from cu_i to uu_j, respectively.

While f_j is utilized by cu_i for DL transmission, uu_j is interfered by the transmitter bs_b's transmission power. Thus, the interference of uu_j from bs_b at time t is denoted as follows:

$$\text{Intf}_{i,j}^{DL}(t) = P_{b,j}(t) h_{b,j}(t), \tag{3}$$

where $P_{i,j}(t)$ and $h_{i,j}(t)$ represent the transmission power and channel gain from bs_b to uu_j, respectively.

Thus, uu_j's received interference $\text{Intf}_{i,j}$ equals to $P_{i,j}(t) h_{i,j}(t)$ if cu_i is a transmitter, and $\text{Intf}_{i,j} = P_{b,j}(t) h_{b,j}(t)$ if cu_i is a receiver. We represent uu_j's SINR at time t when sharing f_j with cu_i as:

$$\Gamma_{j,i}^{UU}(t) = \frac{\rho_{i,j}(t) P_j(t) g_j(t)}{\sigma_N^u + \text{Intf}_{i,j}}, \tag{4}$$

where $P_j(t)$ and $g_j(t)$ is the transmission power and channel gain for uu_j, respectively. σ_N^u is the unlicensed spectrum noise.

Now, we formulate the dynamic spectrum sharing problem in LTE-Unlicensed as a sequence of static resource allocation problems for each time slot. With the objective of dynamically

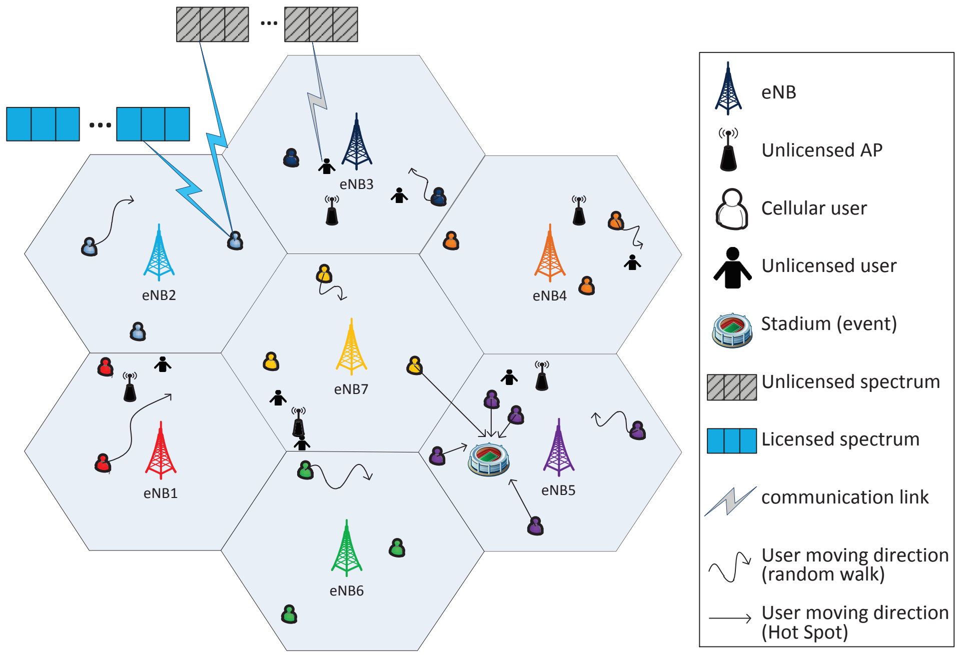

Fig. 1: System Model

maximizing the system throughput, the problem formulation is shown as follows:

$$\begin{aligned}\max_{\rho_{i,j}(t)} & \sum_i \Big(\sum_j \frac{\rho_{i,j}(t)}{\sum_i \rho_{i,j}(t)} f_k \log(1+\Gamma^{CU}_{i,j}(t))\Big) \\ & + \sum_j \Big(\sum_i \frac{1}{\sum_i \rho_{i,j}(t)} f_k \log(1+\Gamma^{UU}_{j,i}(t))\Big), \qquad (5)\end{aligned}$$

s.t. :

$$\Gamma^{CU}_{i,j}(t) \geq \Gamma^{min}_i, \forall cu_i \in \mathcal{CU}, \qquad (6)$$

$$\mathrm{Intf}_{i,j}(t) \leq \sigma_{\text{noise}}, \forall uu_j \in \mathcal{UU}, \qquad (7)$$

$$\sum_j \rho_{i,j}(t) \leq 1, \forall cu_i \in \mathcal{CU}, \qquad (8)$$

$$\sum_i \rho_{i,j}(t) \leq 1, \forall uu_j \in \mathcal{UU}, \qquad (9)$$

Notice that for any uu_j, its associated unlicensed band is pre-assigned, and is denoted as $f_k, \forall f_k \in \mathcal{F}$. (6) is the SINR requirement that any CU should satisfy if to reuse a certain unlicensed band. It limits the interference CU receives from the coexisting UUs on the unlicensed band. (7) represents the maximum interference that any UU can allow resulting from the coexisting CUs on the unlicensed band to guarantee fair coexistence. (8) and (9) are the capacity requirements for CUs and UUs. Each CU can be allocated to only one UU (i.e., one unlicensed band), and each UU is only allowed to matched to one CU.

The formulated problem becomes a sequential mix integer nonlinear programming (MINLP) problems, which are in general NP-hard to solve centrally [21]. In addition, to cope with network dynamics, distributive solutions usually act more quickly with lower computation complexities. Thus, we introduce the matching-based approach as the semi-distributive solution, which will be discussed in the following section.

V. Dynamic Matching Framework

Matching theory, as a mathematical framework attempting to describe the formation of mutually beneficial relations, has been successfully applied to many economic fields. Recently, it has emerged as a promising technique for future wireless resource allocation solutions, which overcomes some limitations of traditional game theory and centralized optimization [22]. The advantages of matching theory include suitable models for various communication issues, preference interpretations for system constraints and efficient algorithms for desired objectives. As a fundamental requirement for wireless systems, the concept of stability should be treated with great attention. Generally speaking, the stability notion in wireless resource allocation applications refers to the situation where no player pairs/groups (e.g., CU and UU pairs) have the incentive to violate the current assignment under the table for their own benefits. The instability caused by such deviations is undesirable in any communication systems. To give a general idea of how matching theory works, we take the classical matching model *stable marriage* (SM) [23] as an example. Assume there are a set of men and a set of women, each of which is called a matching agent. A *preference list* for each agent is an ordered list based on the preferences over the other set of agents who he/she finds acceptable. A matching consists of (man, woman) pairs. A basic requirement, the *stability* concept refers to the case that, in a matching there exists no (man, woman) pair, who both have the incentive to leave their current partners and form a new marriage with each other.

The formulated optimization problem in Section IV, looking from a matching point of view, can be modeled as a one-to-one matching game between the CUs and UUs, which resulting in a many-to-one matching between the CUs and unlicensed bands. Typically, the two-sided one-to-one matching problem has been well studied using the SM model we discussed previously. Different from the traditional SM model,

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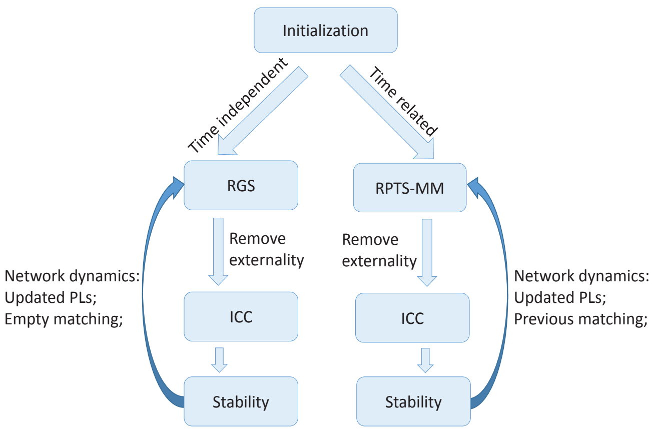

Fig. 2: Matching Implementations

the sequential optimization problems correspond to a dynamic many-to-one matching problem. Intuitively, we can tackle the sequential optimization problems by taking each individual time interval as a traditional SM game, and solving each of them independently over time. This idea will be elaborated in Section V-B. However, in a dynamic network, both the network topology and channel conditions are not isolated in time, and thus there exists some relations between the resource allocations for adjacent times. Instead of solving the optimization problem independently, we may explore the relation between any two time-adjacent networks, and make use of it for the resource allocation. Under such belief, we propose another matching approach, called the random path to stability (RPTS) algorithm, to address the network dynamics. By taking advantage of the relations over time, we can lower the solution cost as compared to the repeated GS approach. The second approach will be discussed in more details in Section V-C. A detailed implementation for both approaches is shown in Fig. 2.

A. Basics of the SM Game

The SM problem is a bipartite matching problem with two-sided preferences. We assume an instance I of the SM problem, which involves a set of men $\mathcal{M} = \{m_1, ..., m_{n1}\}$ and a set of women $\mathcal{W} = \{w_1, ..., w_{n2}\}$. Each man ranks the women from the most favorite to the least favorite based on his preferences, such as personalities, interests, income and so on. Such ranking is called men's preference list. On the other hand, women do the same thing to men. Once the preference lists are built, the players (men/women) take actions according to the lists. Each man or woman is allowed to be matched to at most 1 partner. The final result of this SM matching consists of man-woman pairs, while the objective of the matching diverges. The stability definition for the SM instance is provided in Definition 1.

Definition 1. *Let I be an instance of SM, and $\mathcal{M}$ be a matching in I. A pair (m_i, w_j) blocks M, or is a blocking pair of M, if the following conditions are satisfied relative to M:*

(1) m_i is unassigned or prefers w_j to $\mathcal{M}(m_i)$;

(2) w_j is unassigned or prefers m_i to $\mathcal{M}(w_j)$.

$\mathcal{M}$ is said to be stable if it admits no blocking pair.

$\mathcal{M}(x)$ refers to the partner of x in $\mathcal{M}$, and x can be either a man or a woman.

Similar to the SM matching game, we assume CUs to be men and UUs to be women. Then as the pre-procedure of all matching algorithms, we first establish each player's preference list over the other set of players. With the channel sensing results from both CUs and Wi-Fi APs, CUs and UUs can set up their preference lists. Pay attention that, UUs' preference lists set up are not actually performed by UUs, but by LTE-Unlicensed eNBs and then update to all CUs. More specifically, combining the Wi-Fi MU information from Wi-Fi APs and the CUs' channel sensing results, the LTE-Unlicensed eNBs are able to generate the UUs' preference lists representing the interests of UUs. Thus, the interaction between the CUs and UUs are in fact interactions between CUs and the LTE-U eNBs. The preference of a CU $cu_i, cu_i \in \mathcal{CU}$ over its neighboring UUs $uu_j, uu_j \in \mathcal{UU}$ is based on cu_i's achievable transmission rate when uu_j's unlicensed spectrum f_j. Notice here, that each unlicensed band could be shared with multiple UUs as long as such UUs satisfy the unlicensed transmission regulation. Thus, each unlicensed band can also be shared within multiple CUs, which brings interference between coexisting CUs. However, before CUs join any unlicensed spectrum, they have no idea on the other coexisting CUs. Thus, the preference of cu_i over uu_j (on f_j) at time t is simply assumed to be cu_i's transmission rate when only itself is sharing f_j, and is represented as follows:

$$\mathcal{PL}_{i,j}^{CU}(t) = f_j \log(1 + \Gamma_{i,j}^{CU}(t)). \tag{10}$$

On the other hand, the preferences of uu_j over cu_i at time t is based on uu_j's achievable transmission rate when sharing spectrum with cu_i, which is shown as follows,

$$\mathcal{PL}_{j,i}^{UU}(t) = f_j \log(1 + \Gamma_{j,i}^{UU}(t)). \tag{11}$$

B. Time-Independent Implementation

1) The GS Algorithm: Generally speaking, a stable matching for an SM instance can be achieved by using the GS algorithm. A stable matching is always guaranteed by using the GS algorithm as stated in Theorem 1 [24].

Theorem 1. *Given an instance of SM, the GS algorithm constructs in $\mathcal{O}(m)$ time, the unique man-optimal stable matching, where m is the number of acceptable man-woman pairs.*

The GS algorithm consists of sequential proposing and accepting/rejecting actions. Each iteration starts with the men proposing to the most favorite women (the first entity on the preference list) on their current preference lists. After proposing, the women being proposed to are removed from the men' preference lists. Then the women decide whether to accept or reject the proposals they've received so far based on their preference lists over the men. If the cumulative proposals exceed 1, each woman chooses to keep the man that she favors most, and rejects the rest. This proposing and accepting/rejecting iteration runs for as many rounds as needed until all men are matched or all men preferences are empty,

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and its convergence is provided in [23]. The implementation details of the modified GS in LTE-Unlicensed can be found in Algorithm 1.

Algorithm 1 **Man-oriented GS (GS) Algorithm**

Input:$\mathcal{CU}$, $\mathcal{UU}$, $\mathcal{PL}^{CU}(t)$, $\mathcal{PL}^{UU}(t)$, q
Output: Matching $\mathcal{M}(t)$
  Construct the set of unmatched $\mathcal{CU}_{un}$, set $\mathcal{CU}_{un} = \mathcal{CU}$;
  while $\mathcal{CU}_{un} \neq \emptyset$ and $\mathcal{PL}^{CU} \neq \emptyset$ **do**
    CUs proposal to UUs;
    for all $cu_i \in \mathcal{CU}_{un}$ **do**
      Propose to the first UU it in its preference list uu_j, and remove uu_j from $\mathcal{PL}^{UU}$;
    end for
    UUs make decisions;
    for all $uu_j \in \mathcal{UU}$ **do**
      if uu_j has received proposals no more than 1 **then**
        uu_j keeps the proposal, and remove this CU from $\mathcal{CU}_{un}$;
      else
        uu_j keeps the most preferred proposal, and rejects the rest;
        Remove this favorite CU from the $\mathcal{CU}_{un}$, and add the rejected CUs into the $\mathcal{CU}_{un}$;
      end if
    end for
  end while

2) Eliminating the External Effect: Notice here, for the conventional SM game, a stable matching is guaranteed using the GS algorithm. However, this conclusion is only correct under the canonical matching assumption, which implies that the preference of any player depends solely on the local information about the other type of players. However, for the case, where players' preferences are affected by other players' choices/decision, the matching resulting from the traditional GS algorithm no longer guarantees stability. Any matching with the inter-dependence of players' preferences, is called matching with externality [25]. In fact, the external effect is commonly seen in the wireless resource allocation problems due to users' coexistence interference. Unfortunately, our proposed framework also exists externality, since CUs' performances are indeed affected by the other CUs' choices. For example, if too many CUs are matched to the same unlicensed band, then each of them will be assigned a smaller share (by TDMA) than they expect in the preference list, in which case some CU may have the incentive to change to some unlicensed band (i.e., a different UU) that is not assigned any CU or assigned with less CUs. In addition, each CU is only admitted by its matched UU, but are not necessarily acceptable to the coexisting UUs on the same unlicensed band, and vice verse for the UUs on the other admitted CUs. Such many-to-one relationship between CUs and unlicensed bands brings externality in the channel allocation, thus making the resulting matching no longer stable nor valid.

In order to eliminate such externality, we propose the Inter-Channel Cooperation (ICC) strategy to validate and re-stabilize the matching. As a first step, those invalid sharing, i.e., if a CU is not admitted by at least one of the UUs on the allocated unlicensed band, should be forbidden or removed. As we have discussed before, eNBs are representing the UUs/unlicensed bands to interact with CUs, thus after the matching using GS, eNBs can help find out those invalid CUs/UUs. Then, such invalid sharing are removed by eNBs informing both the related CU and UU, and also help update their preferences by removing invalid players from the lists. Such invalid sharing detection requires centralized information and operation, i.e., the assistance of eNBs. The next step, is to re-stabilize the matching. Pay attention that, since UUs are not really involved in the interaction, but represented by eNBs, thus, the whole matching is based on the interest of the CUs. As long as the unlicensed transmission regulation are meet, the allocation strategy should focus on how to further improve CUs' performances. Therefore, at this time point, the external effect can be evaluated from the CUs' perspective only. In other words, it becomes a one-sided "stability" problem. The new "stability", different from Definition 1, relies on the equilibrium among all CUs (i.e., there is no CU that has incentive to make any change). We call this one-sided "stability" as "Pareto Optimality" in matching theory [24]. The definition of Pareto optimal is given as follows.

Definition 2. *Pareto Optimal: A matching is said to be Pareto Optimal if there is no other matching in which some player (i.e., CU) is better off, whilst no player is worse off.*

Accordingly, we provide the new definition of BP for the one-sided matching problems in Definition 3.

Definition 3. *A BP in the one-sided matching: A CU pair (cu_i, cu_j) is defined as a BP, if both cu_i and cu_j are better off after exchanging their partners.*

The basic idea of ICC is described as follows: firstly remove all invalid (CU, UU) pairs. The removed CUs will remain unmatched during the rest of the ICC algorithm. This is because ICC is designed based on the Pareto optimality, which is the one-sided stability. If any (CU, CU) pair would exchange partners, both of the CUs must agree with the exchange (i.e., benefit from the exchange). Now that the invalid (CU, UU) pairs have been removed, meaning these CUs currently have no UU partners (i.e., unlicensed resource), then it is reasonable that no other CU is willing to exchange partner (i.e., unlicensed resource) with such CUs. The second step is to search all "unstable" CU-CU pairs (who have the exchange incentive) regarding the current matching; secondly, check whether the exchange between such a pair is allowed (beneficial to related CUs); thirdly find the allowed pair, which provides the greatest throughput improvement, switch their partners, and update the current matching; then keep searching "unstable" CU-CU pairs until the trade-in-free environment is reached. The detailed ICC algorithm is illustrated in Algorithm 2.

In Algorithm 2, we transform the current matching $\mathcal{M}$ (i.e., $\mathcal{M}(t)$ generated by GS) into $\mathcal{M}'$. We define $\mathcal{M}(cu_{i1}) = uu_{j1}, \mathcal{M}(cu_{i2}) = vu_{j2}$. The utility of cu_i is represented as $U(cu_i) = f_j \log(1+\Gamma_{i,j}^{CU})$, and $\Delta U(cu_i) = U(cu_i)' - U(cu_i)$, where $U(cu_i)'$ is the utility after exchanging partner with

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Algorithm 2 Inter-Channel Cooperation (ICC) Strategy

Input: Existing matching $\mathcal{M}$, updated preference lists $\mathcal{PL}^{CU}(t)$ w.r.t. $\mathcal{M}$;
Output: Stable matching $\mathcal{M}'$.

```
M' = M;
Remove all invalid (CU, UU) pairs;
while M' is not Pareto optimal do
    Search the set of "unstable" CU-CU pairs BP(t) based on PL^CU(t);
    for all (cu_i1, cu_i2) ∈ BP(t) do
        if ∃cu ∈ M'(uu^k1_j1) ∪ M'(uu^k2_j2), ΔU(cu) < 0 then
            (cu_i1, cu_i2) are not allowed to exchange partners;
        else
            (cu_i1, cu_i2) are allowed to exchange partners;
        end if
    end for
    Find the optimal BP (cu*_i1, cu*_i2);
    cu*_i1 and cu*_i2 switch partners;
    M' ← M' / {(cu*_i1, M'(cu*_i1)), (cu*_i2, M'(cu*_i2))};
    M' ← M' ∪ {(cu*_i1, M'(cu*_i2)), (cu*_i2, M'(cu*_i1))};
    Update PL^CU(t) based on M';
end while
```

another CU. The optimal BP is defined in (12).

$$(cu^*_{i1}, cu^*_{i2}) = \underset{(cu_{i1}, cu_{i2})}{\operatorname{argmax}} \sum_{cu_{i1}\in\mathcal{M}_t(uu_{j1})} \Delta U(cu_{i1}) + \sum_{cu_{i2}\in\mathcal{M}_t(uu_{j2})} \Delta U(cu_{i2}) \quad (12)$$

where the CU pair (cu_{i1}, cu_{i2}) is allowed to exchange partners. The convergence of ICC is guaranteed by the irreversibility of each switch. The dynamic stability, under the time-related implementation, is reached by adopting the GS+ICC algorithm iteratively in each time slot.

C. Time-Dependent Implementation

Although we can use GS+ICC repeatedly in each time slot to find stable solutions, it is not computationally efficient to do so. Let's consider the case that for two adjacent time slots, the network condition varies very slightly. In other words, only a small number of users' preferences are changed. Under such small network variation, the stable matching also only varies a little bit regarding a small number of players. Thus, instead of redoing the whole matching, we can utilize the relations between the matching of the current time slot and that of the previous slot to transform the previously unstable matching into stable again. There, in this section, we propose an adaptive matching approach: the random path to stability (RPTS), also called the Roth Vanda-Vate (RVV) Algorithm [26]. The basic idea of RPTS mechanism is to use divorce and remarriage operations to transform an existing matching into stable again. Based on the previous matching $\mathcal{M}(t-1)$ at time $t-1$ and the updated preference lists $\mathcal{PL}^{CU}(t)$, $\mathcal{PL}^{UU}(t)$ at time t, RPTS algorithm provides a stable matching $\mathcal{M}(t)$ at time t.

For a SM instance I, consisting of the men set $\mathcal{CU}$ and women set $\mathcal{UU}$. As shown in Algorithm 3, the RPTS algorithm starts from an initial matching M_0, which is the previous matching $\mathcal{M}(t-1)$ of time $t-1$ [1], and finally terminates with a stable matching $\mathcal{M}(t)$ at time t. Each loop of RPTS comes with a matching $\mathcal{M}_i$, and finally terminates with a stable matching. A set A is utilized during the loop iteration of RPTS, which is initially empty. $\mathcal{M}_i|_A$ denotes $\mathcal{M}_i \cap (A\times A)$, and $I|_A$ denotes the sub-instance of I obtained by deleting every member of $(\mathcal{CU}\cup\mathcal{UU})/A$, including the preference lists. The loop in RPTS iterates as long as $\mathcal{M}_i$ is not stable in I. During each iteration, if there's a blocking pair (a_i, b_j) in such that $a_i \notin A$ and $b_j \in A$, procedure *add* is called with parameter a_i. Otherwise, the *satisfy* procedure is called with parameters a_i and b_j ($a_i \notin A, b_j \notin A$). Notice here, a_i can be either a man or a woman, and similarly for b_j. The two procedures *add* and *satisfy* are maintained to ensure: 1) no member of A is assigned in $\mathcal{M}_i$ to a member outside of A; 2)$\mathcal{M}_i|_A$ is stable in $I|_A$.

In the *add* procedure, a_i is either a man or a woman, which doesn't belong to A. Our task is to ensure that upon the arrival of a_i, the matching can be restablize so that $\mathcal{M}_i|_A$ is again stable in $I|_A$. We start by divorcing the pair $(a_i, \mathcal{M}_i(a_i))$ if a_i is assigned in $\mathcal{M}_i$, and add a_i to the set A. If a_i, as the current proposer, is a blocking agent (i.e., involved in a blocking pair) in $(I|_A, \mathcal{M}_i|_A)$, we search the best blocking pair (a_i, b_i) in $(I|_A, \mathcal{M}_i|_A)$ w.r.t. a_i's preference list. This b_i must belong to A, and will be divorced from $\mathcal{M}_i(b_i)$ if it's assigned in $\mathcal{M}_i$. Then this $\mathcal{M}_i(b_i)$ becomes the next proposer, and we can marry (a_i, b_i) in $\mathcal{M}_i$. The while loop continues as long as the current proposer is a blocking agent in $(I|_A, \mathcal{M}_i|_A)$.

In the *satisfy* procedure, $a_i \notin A$ and $b_j \in A$, and we assume a_i, b_j to be m_i, w_j. Our task is to satisfy both w_i and w_j. We start by adding w_i and w_j to A. If m_i/w_j is assigned in $\mathcal{M}_i$, we divorce it from its partner $\mathcal{M}_i(m_i)/\mathcal{M}_i(w_j)$. Their partners (if any) will remain unassigned. Then we add this blocking pair (m_i, w_j) to $\mathcal{M}_i$.

Algorithm 3 Random Path To Statbility (RPTS) Algorithm

Input: Stable matching $\mathcal{M}(t-1)$ in the previous time $t-1$
Output: Stable matching $\mathcal{M}(t)$ at time t

```
Initialization:
M_i = M(t-1), A = ∅;
while M(t) is not stable in I do
    if There exists (a_i, b_j) ∈ bp(I, M_i) such that a_i ∉ A, and b_j ∈ A then
        add a_i;
    else
        choose (m_i, w_j) ∈ bp(I, M_i);
        satisfy (m_i, w_j);
    end if
end while
M(t) = M_i
```

The dynamic stability, under the time-dependent implementation, is reached by adopting the RPTS+ICC algorithm

[1]We assume the initial matching $\mathcal{M}_0$ to be empty.

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Algorithm 4 ***add*** **procedure for RPTS algorithm**

Input: a_i,$\mathcal{M}_i$
Output: A,$\mathcal{M}_i$

if a_i is assigned in $\mathcal{M}_i$ **then**
  $\mathcal{M}_i = \mathcal{M}_i/\{(a_i, \mathcal{M}_i(a_i))\}$;
end if
$A = A \cup \{a_i\}$;
while a_i is blocking agent in $(I|_A, \mathcal{M}_i|_A)$ **do**
  a_i is the proposer;
  $(a_i, b_i) \doteq bestbp(I|_A, \mathcal{M}_i|_A, a_i)$;
  $a_z \doteq a_i$;
  if b_i is assigned in $\mathcal{M}_i$ **then**
    $\mathcal{M}_i = \mathcal{M}_i/\{(\mathcal{M}_i(b_i), b_i)\}$;
    $a_i = \mathcal{M}_i(b_i)$;
  end if
  $\mathcal{M}_i = \mathcal{M}_i \cup \{(a_z, b_i)\}$;
end while

Algorithm 5 ***satisfy*** **procedure for RPTS algorithm**

Input: (m_i, w_j),$\mathcal{M}_i$
Output: A,$\mathcal{M}_i$

$A = A \cup \{(m_i, w_j)\}$;
if m_i is assigned in $\mathcal{M}_i$ **then**
  $\mathcal{M}_i = \mathcal{M}_i/\{(m_i, \mathcal{M}_i(m_i))\}$;
end if
if w_j is assigned in $\mathcal{M}_i$ **then**
  $\mathcal{M}_i = \mathcal{M}_i/\{(\mathcal{M}_i(w_j), w_j)\}$;
end if
$\mathcal{M}_i = \mathcal{M}_i \cup \{(m_i, w_j)\}$;

iteratively. Regarding the convergence of RPTS mechanism in the SM model, a conclusion is stated in Theorem 2 [26], and the proof is provided as follows.

Theorem 2. *Let $\mathcal{M}_0$ be an arbitrary matching for a SM instance I with N men and M women. Then there exists a finite sequence of matchings $\mathcal{M}_0, ..., \mathcal{M}_s$, where $\mathcal{M}_i$ is stable, and for each $1 \leq i \leq s$, $\mathcal{M}_i$ is obtained from $\mathcal{M}_{i-1}$ by satisfying a blocking pair of $\mathcal{M}_{i-1}$. Moreover, $\mathcal{M}_s$ can be obtained in $\mathcal{O}((N + M)m)$ overall time, where m is the number of acceptable man-woman pairs in I.*

Proof: During each iteration of RPTS, A increases in size by either one (*add* procedure) or two elements (*satisfy* procedure). At the end of each such iteration, we have $\mathcal{M}_i|_A$ is stable in $I|_A$. Hence we are bound to ultimately reach the outcome that $\mathcal{M}_s$ is stable in I (when A increase to the size of $(N + M)$, in which case RPTS terminates.

The complexity of RPTS is obtained by observing that A increases in size by a minimum number of one element at each loop iteration of RPTS. Since $A \leq (N + M)$, it follows that the same upper bound applies to the number of execution of RPTS. Each proposal-rejection sequence during an execution of *add* involves at most m pair of agents. Thus, each iteration of *add* runs in $\mathcal{O}(m)$ time. While each call of the *satisfy* procedure takes $\mathcal{O}(1)$ time (no while loop inside). Thus, the overall computation complexity of finding a stable matching is $\mathcal{O}((N + M)m)$. ■

VI. Performance Evaluation

A. Complexity Analysis

The primary difference between the GS algorithm and RPTS algorithm lies in their adaptability to network dynamics. Each time, the GS algorithm starts from an empty matching and by proposing/rejecting actions to reach a stable matching, while the RPTS algorithm begins with the matching from the previous round and takes the divorce/remarry operations as its path to stability. Apparently, RPTS takes advantage of the relations between matchings in adjacent times. The computation complexity or say iteration times for both algorithms depends on the number of users and how fast the network changes.

As provided in Section V-B, the complexity of GS is $\mathcal{O}(m)$, where m is the total length of all players' preference lists. It makes sense since the worst case of the GS is to traverse each player's preference lists and terminate. However, the termination condition of GS that each of the player has found its stable partner(s) does not necessarily require the traverse of all preference lists. On the other hand, the computation complexity of RPTS is $\mathcal{O}((N+M)m$, as indicated in Theorem 2. Again, it is not necessary for the RPTS that all possible BPs needed to be satisfied. Regarding the ICC algorithm, it is realized by iterative search of the currently best BP and to swap their partners. The complexity of finding all the BPs regarding the current matching, which requires the traverse of all users' preference lists, is bounded by MN comparing operations. On the other hand, since the swap in ICC is irreversible, meaning each two CUs can only swap partners with each other once, the total iterations of BP searches or swaps are bounded by N^2. Thus, the worst case complexity of terminating the ICC algorithm is $\mathcal{O}(MN \times N^2)$ or simplified as $\mathcal{O}(N^3M)$. However, the actual computation cost is not necessarily as high as the theoretical analysis. In the simulations, we have also performed the practical iteration times of the ICC algorithm.

Theoretically, RPTS has higher complexity than GS in the worst case, however we should not ignore the piratical implementation. The nature of the GS structure decides that it does not require any initial matching. However for RPTS, it can actually take advantage of the previous matching, and transform it into stable instead of transforming an empty matching. Thus, intuitively if some existing pairs from the previous matching are reserved for the current period, then RPTS can save the cost of satisfying these stable pairs. For example, if the previous matching is still stable for the next time period, then no BP/FPBP needs to be satisfied, meaning RPTS actually takes no action. Thus, the actual implementation complexity for GS and RPTS may differ from the theoretical analysis. In practice, the actual complexity depends on many complicated network factors, such as the user velocity, network density and so on. To best evaluate the complexity for both algorithms in wireless communication field, we quantify the complexity (convergence) by counting the number of new connections between (CU,UU) pairs that attempted to be set up during the whole matching procedures. However, these new

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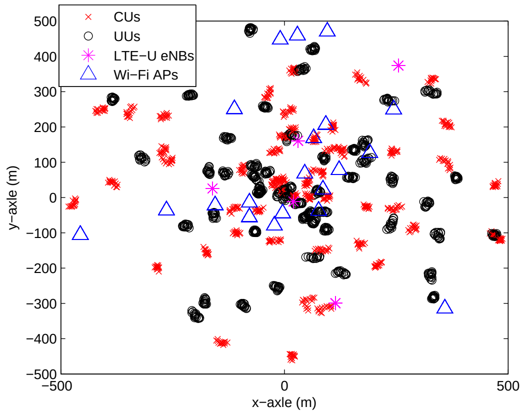
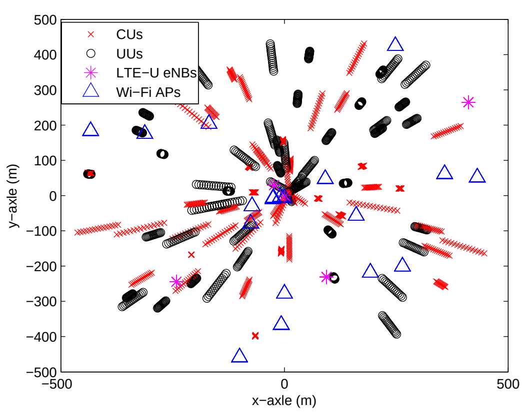
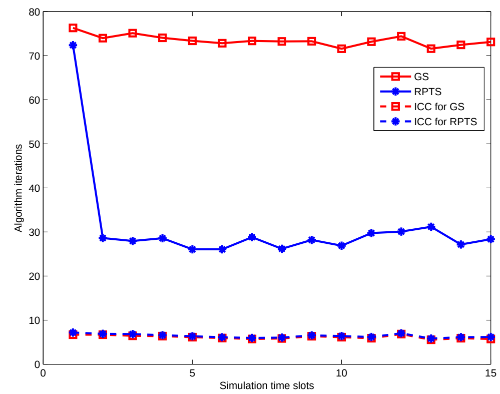


(a) RWP mobility.

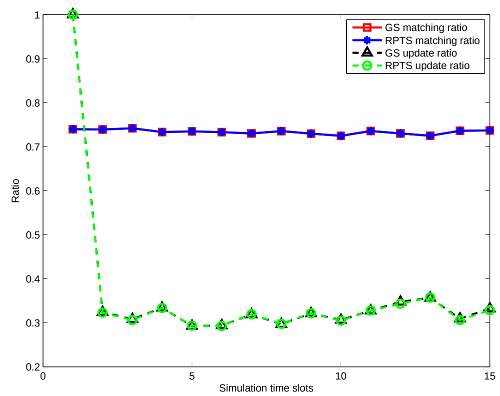


(b) HotSpot mobility.

Fig. 3: User mobility traces for both RWP&HotSpot.



(a) Computation complexity.



(b) Connection updated ratio.

Fig. 4: Time dynamics in the RWP mobility model.

connections are not necessarily the final stable connections, since during the matching, a partnership may break up due to the deviation from any player who receives a better choice. However, building such a potential new connection requires the exchange of information through communications at both ends of the link. As we know, communication overhead is one big concern in protocol/mechanism design w.r.t. both cost and time efficiency. Thus, numerating the number of new potential link set up is in fact a reasonable measurement of the complexity cost for practical implementation. More details of both algorithms' performances are discussed in Section VI-B.

B. Experimental Set-Up

In this simulation, we have adopted two mobility models to test our proposed algorithms. Among many mobility models, the RWP and HotSpot models represent unpredictable and predictable user motion, respectively. The RWP model is a popular mobility model to evaluate mobile ad hoc network routing protocols due to its simplicity and wide availability. In the RWP model, the movement of nodes is governed in the following manner: each node begins by pausing for a fixed duration. Then each node selects a random destination and a random speed between 0 and the maximum velocity. The node moves to this destination and again pauses for a fixed period. This behavior is repeated until the end of simulation [27]. On the other hand, the HotSpot model is also commonly seen. For example, people go to different places for work, dining, shopping and so on, and thus hotspots are formed. More specifically, in the HotSpot model [28], users are initially placed in the neighborhood of a point, which is called the event point. In this motion, each user moves toward the closest event point, never going closer than a minimum separation distance from the event point. Then after a fixed time interval from the start of the event (i.e., the completion of the event), users return to their original locations. Users move at a random speed between 0 and the maximum velocity, which can be changed for topology analysis.

We simulate a cellular network consisting of $B_1 = 5$ eNBs randomly distributed within a circular area with radius of $R = 0.5$ km. The number of CUs and UUs, namely N and M, are within the range from 30 to 65, and are initially randomly distributed within the network. The number Wi-Fi APs is set as and $B_2 = 20$. We assume the total number of unlicensed spectrum as $K = 20$. The K unlicensed bands are randomly allocated to the M UUs. The performances of the GS and RPTS algorithms are evaluated under two mobility patterns: 1) RWP model, 2) HotSpot model. We set the simulation time slot ΔT to be 10 ms, which is selected according to the time scale of the channel slow fading. Compared with the channel fading time scale, users mobility time scale are relatively large. In order to exhibit the influence of both channel change and user movement on the resource allocations, we have made some assumptions to suit the time scale of user mobility models to that of channel fading. In the RWP model, the stop time is set as 2 ms for all users. In the HotSpot model, the fixed time interval (from the start of the event to the end) as 300 ms, which is long enough to cover 15 simulation periods so that during this time interval users are either gathering or leaving the event point. We set the total simulation time for each experiment as 150 ms, i.e., 15 time slots[2] The maximum velocities for both RWP and HotSpot model are set to 50 m/s for CUs, while for UUs, the velocity is set as 10 m/s. An illustration of the user mobility traces are shown in Fig. 3 for both RWP and HotSpot models [3]. The bandwidth of each unlicensed band is set within $[2, 4]$ MHz. The SINR requirement for CUs is a uniform random distribution within $[20, 30]$ dB. While the maximum interference for VUs is -90 dBm (the noise level of unlicensed spectrum). For the propagation gain, we set the pass loss constant C as 10^{-2}, the path loss exponent α as 4, the multipath fading gain as 1, and the shadowing gain as the log-normal distribution with 4 dB deviation [29]. The channel conditions are assume to change every 10 ms time slot. The fast fading is assumed to be static during each time slot.

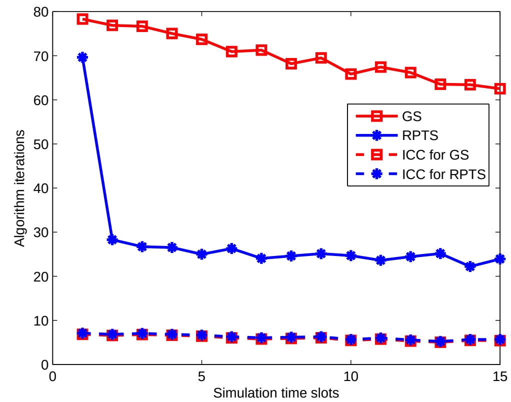
C. Experimental results

We first analyze the impact of network dynamics on the resource allocations, caused by the channel change and user mobility, in the time frame. Fig. 4, Fig. 5 and Fig. 6 evaluate the time dynamic performances of GS, RPTS and ICC algorithms, w.r.t. the computation complexity, matching update ratio, and system throughput.

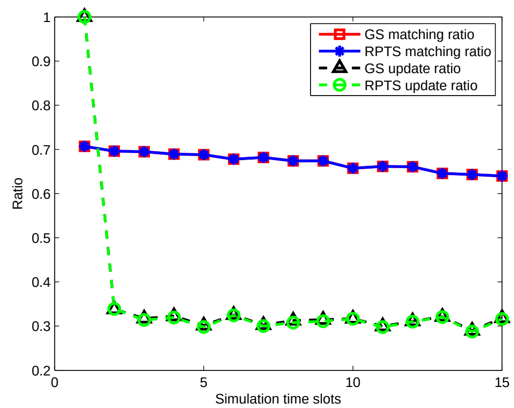
The complexity (measured by the number of new connections as discussed in Section VI-A) of the three proposed algorithms are compared under RWP and HotSpot patterns in Fig. 4(a) and Fig. 5(a), respectively. Apparently, the RPTS algorithm achieves a much lower complexity than GS under both mobility models during the whole 150 ms simulation period, which is about only 40% complexity of GS except at the starting point. As the theoretical analysis indicate that RPTS has higher complexity than the GS algorithm, however the practical cost depends on the network implementation. Thus, it demonstrates the effectiveness of the RPTS algorithm in transforming a random matching into stable with lower complexity than the GS algorithm. For the starting point, it's reasonable that RPTS has a relatively high cost, still lower than the GS, since it starts from am empty matching. Comparing the two curves of the ICC algorithm implemented after the GS and RPTS in both Fig. 4(a) and Fig. 5(a), they achieve similar results, and the complexity costs for both are about 8 averagely. It means that using the proposed ICC procedures, only around 8 actual swaps are needed to re-stabilize the whole matching. In the HotSpot model, the complexities for all three algorithms slowly decreases as time evolves, which is caused

[2]This time interval is much shorter than practical case of user gathering or moving randomly, which is specifically shortened to model the impact of the motion pattern on the designed protocols.

[3]To better illustrate the user mobility traces on the drawing figures, we have tuned the maximum speeds so that the mobility traces can be evident to see.



(a) Computation complexity.



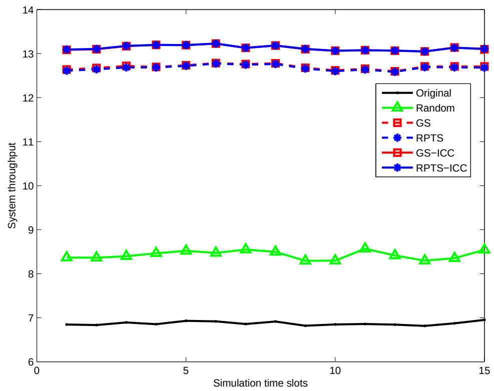
(b) Connection update ratio.

Fig. 5: Time dynamics in the HotSpot mobility model.

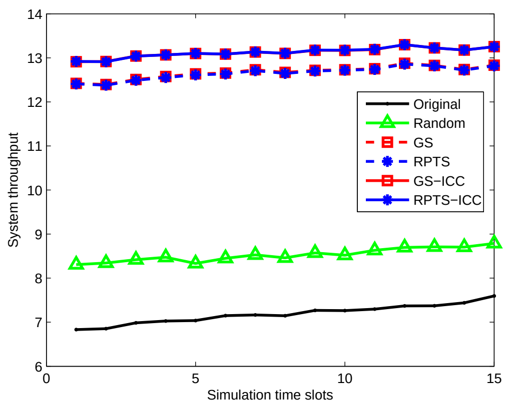
by the slight decrease of the matching ratio as indicated in Fig. 5(b). This is reasonable since in the HotSpot model, CUs are gathering toward the event point (faster than UUs) and thus less distributively, which gives CUs less options as most UUs are still far from the event location.

In Fig. 4(b) and 5(b), we have evaluated both the user matching ratio and the matching update ratio by using GS and RPTS. The user matching ratio represents the percentage of CUs who are allocated with a proper unlicensed band by sharing with an UU. As indicated in both figures, GS and RPTS achieve similar matching ratio, which is as high as 75% in the RWP and 70% in the HotSpot model, averagely. The other two curves evaluate the percentage of updated users by comparing the matching results in the previous and current simulation slots. Again, both algorithms have similar performances, which are around 30% averagely. The update ratio at the starting point for both GS and RPTS is 100%, since we assume to start with an empty matching.

For the throughput performance, we compare the GS and RPTS, with five methods: GS-ICC, RPTS-ICC, Random, Original and Optimal. The GS-ICC and RPTS-ICC methods refer to the cases that ICC is used after GS and RPTS, respectively. The Random method refers to randomly allocating the UUs to the CUs, while the Original method refers to the case that no spectrum sharing happens. In the RWP model, as shown in Fig. 6(a), the average system throughput is evalu-



(a) RWP model.



(b) HotSpot model.

Fig. 6: Average system throughput comparison.

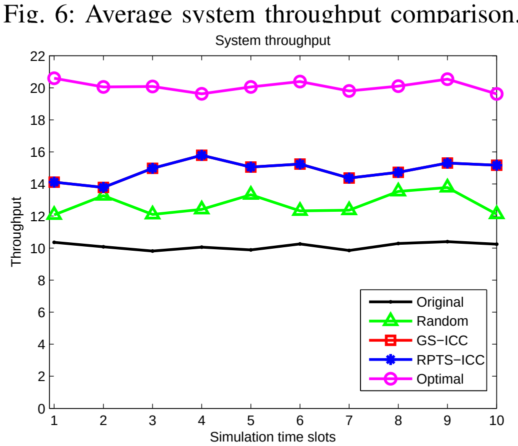
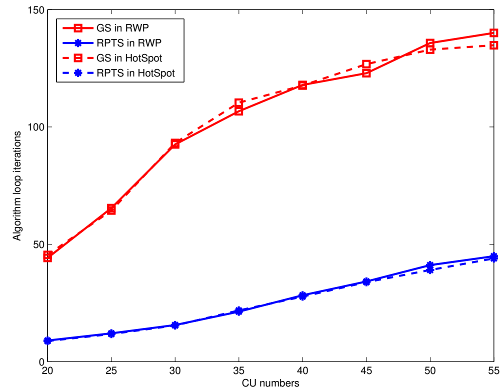
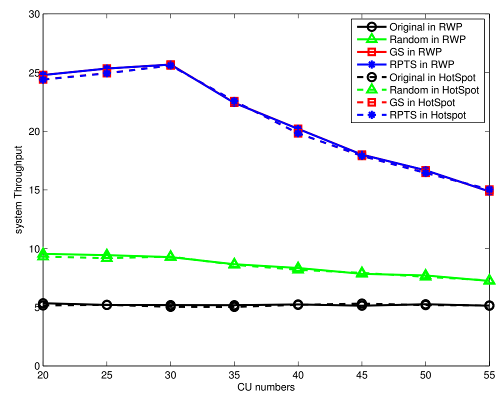


Fig. 7: System throughput comparison with optimal solution.

ated. Apparently all four matching algorithms outperform the Random and Original methods a lot. GS and RPTS achieve similar throughput performance, and the same conclusion can be drawn for GS-ICC and RPTS-ICC. Apparently, with ICC procedures, the system throughput is further improved for either the GS or RPTS algorithm. Specifically, the average system throughput achieved by GS+ICC or RPTS+ICC is about 86% higher than the Original method, and 53% higher than the Random allocation. We have also compared the performance of the proposed methods with the optimal result in Fig. 7. The optimal result is found by the brute force



(a) Computation complexity.



(b) System throughput.

Fig. 8: CU density dynamics in RWP&HotSpot mobility model.

approach, which is time-consuming. Thus, the number of CUs and UUs are set as $N = 4$ and $M = 4$, $B_1 = 2$, and $B_2 = 2$. Averagely, both RPTS-ICC and GS-ICC can achieve 75% system throughput of the optimal result.

Except the time dynamic analysis, we have also evaluated the impact of network density and mobility velocity changes to the resource allocations. As shown in Fig. 8, we change the network density by adding more users, including both CUs and UUs, to the network without adding any eNBs, Wi-Fi APs, or unlicensed bands. We add 5 CUs and UUs to the network by staring with $N = M = 20$ and end at $N = M = 65$. We average the performance result of 150 ms time period for each network density. The unlicensed band number is set as $K = 30$. As shown in Fig. 8(a), the complexity of GS, RPTS and ICC all increase as more users join the network, since more users brings more options. In addition, the complexity of GS grows faster than the RPTS, which demonstrates good scalability of the RPTS algorithm. For system throughput, as shown in Fig. 8(b), the average user throughput increases before N/M reaches K and decreases as N/M is greater than K. The peak point is when each unlicensed band can actually accommodate one CU, and when more CUs come after this point, the unlicensed bands will be shared between multiple CUs by TDMA.

We changed the maximum velocity value in both mobility

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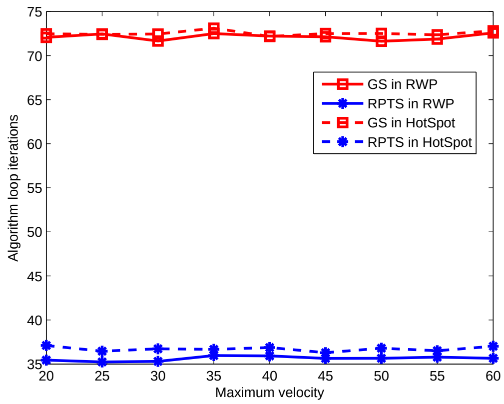
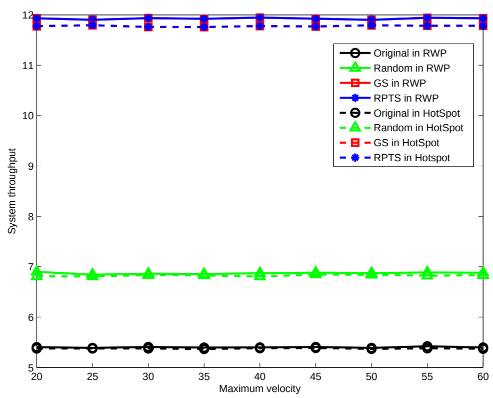


(a) Computation complexity.



(b) System throughput.

Fig. 9: CU velocity dynamics in RWP&HotSpot mobility model.

models to test our proposed algorithms. As shown in Fig. 9, we increase the maximum use velocity from 20 m/s to 60 m/s by step of 5 m/s for the CUs. Apparently, the velocity changes does not necessarily has impact on the computation complexity or the system throughput, which on the other hand validate that our assumptions in the two user mobility models have no impact on the results although slightly different from the practical case.

VII. Conclusion

In this work, we have studied the dynamic resource allocation problem in the LTE-Unlicensed in a semi-distributive manner. The SM matching model well has interpreted the two-sided feature of the resource allocation system. The proposed GS and RPTS algorithms provide close optimal system performance, while both guaranteeing system QoS requirements and stability. Specifically, the RPTS algorithm, different from the repeated static resource allocation GS, achieves better performance w.r.t. the practical implementation complexity, CU matching ratio, and matching update ratio. In other words, the RPTS algorithm is more adaptable than the GS algorithm under both unpredictable and predictable mobility patterns in providing paths to dynamic stability in the LTE-unlicensed.

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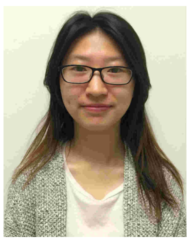

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