A Two-Stage Matching Game and Repeated Auctions for Users Admission and Channels Allocation in 5G HetNets

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ABSTRACT The fifth-generation (5G) wireless cellular networks aim to increase the users capacities and quality of experience as well as integrating different wireless bands and modes of access. The introduction of cognitive radio technology and heterogeneous networks (HetNets) as part of the architecture of the 5G aims to efficiently reuse the available spectrum. This paper presents a two-stage framework based on matching theory and auction games with the objective of efficiently admitting secondary users in the wireless scene. At the first stage, a fast convergence matching game for the users admission problem in 5G HetNets is considered, where secondary users are associated to appropriate secondary base stations. These base stations access the available primary spectrum on behalf of its associated users in the next stage, namely a repeated modified English auction. Results show the existence of a stable matching point for the users admission game and a Walrasian equilibrium point for the repeated auctions. In addition, extensive simulations are performed to compare the proposed repeated auction against the single auction and the matching theory. It is proven that the repeated auction game outperforms the single auction game and matching game in terms of the occupancy of primary channels and the satisfaction of the secondary users.

INDEX TERMS 5G, HetNets, cognitive radio, users admission, channels allocation, matching theory, stable matching, English auctions, Walrasian equilibrium.

I. INTRODUCTION

The fifth-generation (5G) mobile communication systems are envisioned to target three main factors, namely ultra reliable low latency communication (URLLC), enhanced mobile broadband service (eMBB) and accommodating massive machine type communication (mMTC) [1] [2]. To achieve these goals, different requirements and design aspects should be considered. Considering eMBB systems, massive capacity, and extremely high data rates are some of the challenges imposed. Deep coverage is another challenge while introducing mMTC in 5G networks. For URLLC, mobility and resilience against varying channel, possible latency, and delay sources should be considered.

To mitigate the above challenges, innovative enabling technologies are considered for the 5G. One of these technologies is dense heterogeneous networks (HetNets). Generally, a HetNet can be described as a composition of cellular macro-base stations with a relatively high transmission power overlaid (or underlaid) with low power base stations having smaller coverage areas. The low power base stations, including picocells, femtocells, and relay nodes, are commonly referred to as smallcells [3], [4]. Deployment scenarios for HetNets include; multicarrier deployment, carrier aggregation, and co-channel deployment [4]. In this work, we consider multicarrier deployment, where femtocells are deployed on carrier frequencies different from those of the macrocell network. This channel deployment technique is effective in avoiding the interference caused by the macro base stations on the femtocell networks. One drawback is that multicarrier deployment is not very spectrum efficient.
compared to other existing scenarios. Hence, we consider cognitive radio (CR) technology to maximize the spectrum efficiency [5]. One useful application of HetNets is the ability to integrate different access technologies. For example, the macrocell network could be based on cellular technology and the low power access points are based on wireless local area networks (WLAN) as in [4, and references therein], [6].

CR is an innovative concept for spectrum sharing in wireless networks. It is used to enhance the spectrum efficiency by alleviating the spectrum scarcity problem, increasing the overall data rate, network capacity, which leads to introducing an enhanced structure multi-tier 5G HetNet [7], [8]. Generally speaking, the spectrum is divided into licensed and unlicensed spectrum. The unlicensed spectrum is fully occupied by unlicensed devices, even though the licensed spectrum is normally underutilized. Sharing the licensed spectrum with the unlicensed (secondary) users, if done in an well-planned manner, can lead to a notable increase in the spectrum efficiency. Typically, spectrum sharing networks includes four phases, spectrum sensing, spectrum allocation, spectrum access, and spectrum handoff [7]. In the spectrum sensing phase, secondary users (SUs) sense the available spectrum to find out if it is occupied by a primary user (PU) or not. To measure the accuracy of the spectrum sensing, two metrics are adopted, mis-detection probability and false alarm probability. During the spectrum sensing phase, SUs collect information about the available spectrum, including: spectrum occupation, channel gain, and PUs power [8]. In the spectrum access phase, the SUs can access the licensed spectrum using one of the three techniques, namely: dynamic exclusive, open access, and hierarchical model [2]. The hierarchical model consists of overlay, underlay and interweave techniques. Although CR inclusion in 5G HetNets considerably improves the performance of the network, some challenges arise, including: SUs association, spectrum allocation while protecting primary resources, power management, and interference mitigation.

A. RELATED WORK

Efficient user assignment and spectrum allocation algorithms were proposed in literature for various scenarios, e.g., in [9], the authors presented a comprehensive survey on user association algorithms designed for HetNets, including: stochastic geometry, combinatorial optimization, game theory, and matching theory.

Several recent literature about user association considered matching theory, due to its low complexity [10]–[16]. Matching theory provides a mathematically tractable solution for the combinatorial problem of matching players in two distinct sets, depending on the individual information and preference of each player [10]. The work in [11] considered an early acceptance matching game for the users association problem and found a near-optimal solution. While authors in [12] used a Boston school mechanism for the uplink user association problem in HetNets. Two many-to-one matching games were proposed in [13] for optimal user association in the uplink and downlink in 5G multiple radio access technology ultra-dense networks. The work in [14] considered the problem of joint user association and channel assignment with proportional fairness signal-to-interference-plus-noise ratio (SINR) based power allocation in downlink multicell non-orthogonal multiple access (NOMA) networks. Two many-to-one matching algorithms were proposed to associate users with base stations and perform channel assignment. However, this work did not consider the association of users to small base stations which are more energy efficient [3]. Moreover, an efficient channel reuse algorithm was not considered in [14], since its goal was to assign users to channels already available at each base station. In [15] a joint user association and resource allocation in the uplink cognitive femtocell network using matching theory was introduced. Only a single-tier channels allocation was considered.

Regarding the spectrum allocation issue, matching theory, game theory, and auction theory were introduced as a solution for the problem [17]–[30]. Matching theory was considered for modeling the spectrum allocation problem. Single-tier channels allocation in [17] studied a one-to-one matching game between SUs and channels. The work in [18] considered a many-to-one matching game for multiple channels allocation to the same SUs. The work in [18] also considered the achievable rate as the SUs utility and the interference multiplied by the fee for channel usage as the utility of the primary channels. On the other hand, the work in [19] aimed at maximizing the SUs sum rate for non-orthogonal multiple access HetNets through a many-to-one matching algorithm for the spectrum allocation problem. Authors of [20] formulated an optimization problem to maximize the network sum-rate in a heterogeneous cloud radio access networks (H-CRAN), where two many-to-one matching games were used for resources allocation, and devices association. The matching theory used in [17]–[20] aimed to maximize the resource compensation. However, in many practical scenarios, the monetary compensation for the primary users, which is most conveniently modeled by game theory, can be of more economic value.

Game based spectrum allocation can be generally treated by economic games. In fact, multiple games can be used to address the allocation, e.g., in [21] a Bertrand game modelled the interaction between licensed users to set the prices of the channels. Then, a bargaining game was used to model the competition between SUs over the available priced spectrum, and finally a Stakelberg game modelled the different tiers in the network. The work in [22] used a coalition formation game along with a matching game for the problem of channels allocation over ultra-dense femtocell networks. The coalition game was used to form a cooperation between FBSs, which mitigated the co-channel interference, while the matching game was used for subchannel allocation per coalition. In [23], a two-stage distributed channel allocation algorithm was proposed to study the downlink channel allocation in device-to-device (D2D) assisted small cell networks with heterogeneous spectrum bands. A potential game
was used to get the stable matching between different SUs and channels in different frequency bands, and a coalition game for forming coalitions between D2D users and SUs through D2D pairs transferring. However, splitting the spectrum management problem into multiple stages increased the complexity of the proposed algorithms.

Auction theory was widely discussed for the spectrum allocation in wireless communication networks as well. [24] proposed multi-winner spectrum allocation mechanism which deployed a centralized single-sided sealed-bid auction, where SUs submitted their bids privately to an auctioneer. Then, the auctioneer developed algorithms for the pricing and the winner determination. A double-auction-multi-winner mechanism was introduced in [25], where both the SUs submitted bids while the PUs submitted ask values. An auctioneer decided the clearing price based on the received bids and asks. Traditional auction mechanisms fail to model the problem of multiple channels allocation over SUs with non-uniform demands. Combinatorial auctions on the other hand, allows SUs to request a quoted number of channels based on their requirements. The requests are either met or denied by the primary owners. Cognitive femtocell base stations were treated as secondary base stations competing to win a channel from a massive MIMO macro-base station using auction game [26]. In [27] auction was used to maximize the achievable sum data rate through resource block and power level assignment for the underlay users. The authors in [28] used a two-round combinatorial auction for distributed resource allocation in D2D underlay cellular networks. In the first round, each bidder submitted its offer for each channel. In the second round, the results obtained were optimized by considering the interference received from other users. A comparison between matching theory and combinatorial auctions for multiple channels allocation to a single SU was conducted in [29]. A survey on the application of Stackelberg game in resource allocation in cognitive radio was conducted [30].

In general, pricing models, including auctions, focuses on the monetary gain during the channels allocation process, while protecting PUs interests [31]. However, to the best of our knowledge, little literature considered the distributed reuse of channels from heterogeneous multi-tier primary base stations (PBSs) to cognitive secondary base stations (SBSs). In our proposed model, we assume that the primary system consists of the macro base stations (MBSs) tier and the femto base stations (FBSs) tier together, while the secondary system consists of the SBSs and the SUs. The femtocell network and the macrocell network benefit from the multicarrier deployment model, where each of the MBSs and the FBSs have different carrier frequency channels. The SBSs have the same coverage areas and power capabilities as pico base stations [4], [6]. The previous work on distributed multi-tier resource allocation considered the existence of a single source of channels, MBS only, and different tiers trying to access the available channels [27]. In this paper, we extend our work in [32], which proposed a users admission algorithm using matching theory, besides a channels allocation algorithm using combinatorial auctions, that considered the existence of multiple channels resources; MBSs, and FBSs. Here we modify the SBSs utility in the matching game to consider the effect of the matching stage on the FBSs as well as the MBSs. Also, we repeat the auction in [32] to provide better channels usage and users satisfaction as described latter in Section I-B.

B. CONTRIBUTIONS AND ORGANIZATION

Inspired by the aforementioned potential benefits of CR technique, this paper investigates the application of CR in 5G HetNets for spectrum efficiency improvement. We consider the issues of SUs assignment to a number of cognitive SBSs, and the allocation of primary macro channels or primary femto channels to these SBSs to satisfy the requirements of their associated users. The channel assignment to secondary base station should follow the well known rule of operation of cognitive radio, namely, keeping the quality-of-service of the PBSs unaffected. Due to the dependency of the channels allocation phase on the results of the SUs admission to the SBSs, we introduce a two-stage algorithm for the considered problems, namely users association and channels allocation, where the number of channels required by each SBS depends on the number of SU s assigned to it and their requirements. Moreover, optimizing users admission and channels allocation jointly adds computational complexity to the users admission stage, increasing the complexity of the whole system.

The key contributions in this paper are summarized as:

- We consider a joint users admission and a distributed multi-tier channel allocation, where the realistic different nature, and requirements of the different tiers in 5G HetNets; MBSs, FBSs, and SBSs, are taken into consideration. MBSs are assumed to have relatively higher powers, larger users capacity, and more interference tolerance in comparison to FBSs. In order to fulfill the associated SUs rates, the SBSs try to access the femto channels using the underlay scheme to avoid harming the femto users, while the macro channels are accessed in a hybrid manner; using either interweave, or underlay schemes.
- A fast convergence many-to-one matching game is introduced for the downlink admission of SUs to a number of SBSs, which considers multi-tier. Each SBS promises each SU a certain data rate based on which the SUs propose to that SBS. The utility of the SBSs considers the SUs requirements and the possible interference on the primary system; including both MBSs and FBSs taking into account all possible sensing errors. This is an extension of our previous work [32], in which the utility focused on the significant interference incurred on the MUs only, where the access scenario is in underlay mode.
- A repeated modified English auctions for the multi-tier channels allocation is proposed, where each SBS is assigned a number of primary channels, belonging to
either MBS or FBS. The utility is the weighted sum of the SBSs achievable rate, and the PBSs achievable rate, where the PBSs include both the MBSs, and the FBSs. Compared to the single auction used in our previous work [32], repeated auctions give better performance, as elaborated in Subsection V-B.

Simulations show the existence of a bounded stable matching point after the admission game and a Walrasian equilibrium point after the channels auction. It is also proved that the repeated auctions achieve 100% satisfaction of the SBSs requirements and an overall enhancement in the average SBSs sum rate if the available number of channels is large enough, and an approximate 100% channels occupation for a smaller number of channels. A comparison between single auction in [32] and the proposed repeated auctions is conducted, to study the convergence of the proposed model, SBSs average achieved data rate, channels occupation, and SBSs satisfaction. We also apply a many-to-one matching algorithm to the channels allocation problem to compare between matching theory and single auction and repeated auctions. Compared to the matching game, repeated auctions game is proved to give better percentages of satisfied SBSs, as well as better unused macro and femto channels percentages. Moreover, single and repeated auctions also helps in load balancing between macro and femto usage, by the help of the prices set to each channel, unlike the matching game, in which no pricing strategy is assumed.

The rest of the paper is organized as follows. In Section II, the considered system model and assumptions are described. The user admission game, with the SUs and SBSs utilities and the matching algorithm, is introduced in Section III. The channels allocation game between the SBSs and the PBSs, along with the required utilities, and the auctions mechanism are presented in Section IV. Section V illustrates the simulation parameters and results of the presented system, followed by the conclusion of the proposed work in Section VI. Table 1 summarizes the used symbols and notations.

II. SYSTEM MODEL

The 5G HetNet system model considered consists of a single macrocell, a number of femtocells, a number of SBSs, and a number of SUs in its range as illustrated in Figure 1.

The MBS has a number of macro primary users (MPUs) already assigned to it. For the model development in this paper, we consider the downlink case, where orthogonal-frequency-division-multiple-access (OFDMA) is adopted. Hence, each MPU is assigned a single macro channel at a time. However, the proposed work is extendable for multiple users per channel. $F = \{1, 2, \ldots, f, \ldots, F\}$ represents the set of FBSs. Unlike the MBS, each FBS has a single user assigned to it served by a single channel [4], [6]. Set $K = \{1, 2, \ldots, k, \ldots, K\}$ represents the set of SBSs, while $M = \{1, 2, \ldots, m, \ldots, M\}$ is the set of SUs unmatched to any base station initially.

The locations and average data rate of each SBS are known for all SUs in the system. Each SU is to be matched with

| TABLE 1. Symbols and notations |
|--------------------------------|
| **Symbols**                  | **Description**                                      |
| $p_k$, PBS                    | False alarm probability when SBS $k$ is sensing the PBS |
| $p_f$, PBS                    | Mis-detection probability when SBS $k$ is sensing the PBS |
| $\gamma_{k,n}$, PBS           | Energy detector at SBS $k$ threshold value           |
| $N_s$                         | Number of sensing samples                           |
| $\sigma^2$                    | Noise power                                          |
| $P_{PBS}$                     | PBS transmission power                               |
| $P_{MBS}$                     | MBS transmission power                               |
| $P_f$                         | FBS transmission power                               |
| $|h_{k,PBS}|^2 + \theta_k$     | Channel gain between SBS $k$ and the PBS sensed      |
| $\theta_f$                    | Probability that the MBS is on                       |
| $P_{\text{max}}$              | Probability that FBS $f$ is on                       |
| $\mathcal{T}_{0,n}$, PBS       | Maximum transmission power of any PBS                |
| $P_{\text{actual}}$           | Exact underlying power when SBS $k$ uses channel $n$ |
| $Q_k$                         | Minimum Underlay power when SBS $k$ uses channel $n$ |
| $\mathcal{T}_{m,k,n}$, PBS     | Interference channel gain between SBS $k$ and the MPU $i$ using channel $n$ |
| $R_k$                         | Allowable interference power at the MPUs            |
| $\mathcal{T}_{m,k,n}$, PBS     | Quota of SBS $k$ during the admission game           |
| $R_k$                         | Average rate from SBS $k$ to SU $m$, while using a macro channel $n$ |
| $R_k$                         | Channel gain between SBS $k$ and SU $m$             |
| $R_k$                         | Channel gain between MBS using channel $n$ and SU $m$ |
| $R_k$                         | Average rate from SBS $k$ to SU $m$, using a femto channel $f$ |
| $R_k$                         | Channel gain between FBS $f$ and SU $m$             |
| $R_k$                         | Average rate from SBS $k$ to SU $m$                 |
| $R_k$                         | SU $m$ matching game utility when admitting to SBS $k$ |
| $R_k$                         | Average required bit rate by SU $m$                 |
| $R_k$                         | SBS $k$ matching game utility if it uses a macro channel and is matched to SU $m$ |
| $R_k$                         | SBS $k$ matching game utility if it uses FBS $f$ channels and it is matched to SU $m$ |
| $R_k$                         | SBS $k$ matching game utility when matched to SU $m$ |
| $R_k$                         | Stable matching assignment matrix                     |
| $\mathcal{T}_{k,n}$, PBS       | Set of unmatched SUs during the matching algorithm   |
| $\mathcal{T}_{k,n}$, PBS       | Null set                                            |
| $\mathcal{T}_{k,n}$, PBS       | SBS $k$ required rate after the matching game        |
| $\mathcal{T}_{k,n}$, PBS       | Actual rate from the MBS to SBS $k$ when channel $n$ serves its admitted SU $x_k$ |
| $\mathcal{T}_{k,n}$, PBS       | Actual rate from FBS $f$ to SBS $k$ to serve its admitted SU $x_k$ |
| $\mathcal{T}_{k,n}$, PBS       | SBSs utility during the channels allocation stage, when SBS $k$ uses the MBS channel $n$ |
| $\mathcal{T}_{k,n}$, PBS       | SBSs utility during the channels allocation stage, when SBS $k$ uses the FBS channel $f$ |
| $\mathcal{T}_{k,n}$, PBS       | Maximum number of channels demanded by SBS $k$ |
| $\mathcal{T}_{k,n}$, PBS       | MBSs utility during the channels allocation stage, when SBS $k$ uses the MBS channel $n$ |
| $\mathcal{T}_{k,n}$, PBS       | MBSs utility during the channels allocation stage, when SBS $k$ uses the FBS channel $f$ |
| $\mathcal{T}_{k,n}$, PBS       | FBSs utility during the channels allocation stage, when SBS $k$ uses the FBS channel $f$ |
| $\mathcal{T}_{k,n}$, PBS       | Channel gain between the MBS and its MPU $i$         |
| $\mathcal{T}_{k,n}$, PBS       | Channel gain between FBS $f$ and its user $j_f$      |
| $\mathcal{T}_{k,n}$, PBS       | SBSs utility while using either the MBS channels or the FBSs channels |
| $\mathcal{T}_{k,n}$, PBS       | PBSs utility in the channels allocation stage        |
| $\mathcal{T}_{k,n}$, PBS       | Weighting parameter to increase the priority of SBSs utility over that of PBSs |
| $\mathcal{T}_{k,n}$, PBS       | Joint Utility used in the channels allocation stage prices incrementing factor |
| $\mathcal{T}_{k,n}$, PBS       | Initial channels prices                             |
| $\mathcal{T}_{k,n}$, PBS       | Initial monetary gain of SBS $k$ in auctions        |
| $\mathcal{T}_{k,n}$, PBS       | Initial demand set for SBS $k$                      |
| $\mathcal{T}_{k,n}$, PBS       | Initial excess demand set                           |
| $\mathcal{T}_{k,n}$, PBS       | Set of unsatisfied SBSs during channels allocation  |
| $\mathcal{T}_{k,n}$, PBS       | Set of unallocated macro channels                   |
| $\mathcal{T}_{k,n}$, PBS       | Set of unallocated femto channels                   |
an SBS that promises it with the highest data rate. Each SBS $k$ has a certain quota $Q_k$, that represents the maximum number of users that could be assigned to each SBS during the admission game. Non-identical Quotas of different base stations are assumed.

Assuming time-division-multiple-access (TDMA) mode, each SBS serves its users in different time slots, where the number of slots equals the actual number of users associated with each SBS after the matching game. Multiple channels are allocated to SBSs according to the required rate to serve their users. SBSs are assumed to act as cognitive radio stations are assumed.

Following [29], energy detection is used at each SBS for sensing the primary channels. Each SBS $k$ compares the received power from the PBS to a certain threshold value $\gamma_{th,k}$, knowing the noise level. If the received power is higher than $\gamma_{th,k}$, SBS $k$ assumes the channel is occupied, if not, the channel is assumed to be available. The process is repeated for a number of sensing samples $N_s$. Errors due to the sensing are considered here, where the false alarm probability and the detection probability are related as [29]

$$P_{k,PBS}^{FA} = Q\left(\frac{\gamma_{th,k} - N_s\sigma^2}{\sigma^2\sqrt{2N_s}}\right),$$

$$P_{k,PBS}^{MD} = 1 - Q\left(\frac{\gamma_{th,k} - N_s(\sigma^2 + P_{PBS}|h_{k,PBS}|^2)}{\sqrt{2N_s}\sigma^2(\sigma^2 + 2P_{PBS}|h_{k,PBS}|^2)}\right),$$

where $P_{k,PBS}^{FA}$ and $P_{k,PBS}^{MD}$ are the false alarm and the misdetection probabilities when SBS $k$ is sensing the transmission of the PBS, respectively. $\sigma^2$ is the noise power, $P_{PBS}$ is the transmission power of the PBS, and $|h_{k,PBS}|^2$ is the channel gain between SBS $k$ and the PBS being sensed. $Q(.)$ is the tail probability of the normal distribution, given by

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} e^{-t^2} dt.$$  

Accordingly, four different cases exist while sensing the operation of each base station, as described in Table 2,

i) Correct detection, where the PBS is ON with a probability $\theta_n$ and the SBS senses correctly that it is ON with a probability $(1 - P_{k,PBS}^{MD})$.

ii) Mis-detection, where the PBS is ON with a probability $\theta_n$, but the SBS fails to detect it with a probability $P_{k,PBS}^{MD}$.

iii) False alarm, where the PBS is OFF with a probability $(1 - \theta_n)$, yet the SBS detects a signal with a probability $P_{k,PBS}^{FA}$, and

iv) No false alarm, where the PBS is OFF with a probability $(1 - \theta_n)$, and the SBS correctly detects no signal with a probability $(1 - P_{k,PBS}^{FA})$.

Cases (ii), i.e., mis-detection, and (iii), i.e., false alarm, degrade the benefit of the primary channels and affect the overall system performance.

Macro channels could be accessed either in interweave or underlay schemes, while femto channels are only accessed in interweave scheme. Since, MBs use higher transmission powers and have a higher tolerance to interference caused by the SBSs on their MPUs. However FBSs use transmission powers comparable to that used by the SBSs, thus FPs will suffer from intolerable interference if the SBSs accessed the femto channels using interweave scheme. In the underlay scheme, SBSs use the channels continuously regardless of the presence of macro communication. However, unlike the interweave scheme, where the SBS is free to transmit with its full maximum power $P_{max}$, in underlay scheme when the primary transmission is present, the SBS transmits at a reduced power level to protect the primary transmission from excessive interference.

The underlay power when SBS $k$ uses channel $n$ is calculated as

$$P_{u,k,n} = \min\left(\frac{P_{max}}{|h_{k,n}|^2}, \frac{P_{int}}{|h_{k,n}|^2}\right),$$

where $|h_{k,n}|^2$ is the channel gain between SBS $k$ and MPU $i$ using macro channel $n$, and $P_{int}$ is the allowable interference power at the macro users. Meanwhile, SBSs are allowed to access the femto channels when cases (ii), i.e., mis-detection, and (iv), i.e., no false alarm, are satisfied. Upon using the femto channels, the SBSs transmit with maximum power.

### III. SECONDARY USERS ADMISSION GAME

Initially, for the SUs to join the system, they need to be assigned to a certain SBS that should serve their requirements without affecting the primary communication. Assuming there is a limited number of SBS compared to the number of SUs, a single SBS should be assigned several SUs. However, each SBS has a limit on the maximum number of SUs that it can serve, i.e., its quota $Q_k$. For an SBS $k$, $Q_k$ is randomly

\[ r \in [0, 1] \]

where $r \sim U(0, 1)$ is a random number uniformly distributed between 0 and 1. Each SU $m$ from the SUs set $\mathcal{M}$, with a rate requirement $R_m$, is assigned to a SBS $k$ if $R_m \leq Q_k$. The SUs set $\mathcal{M}$ is divided into two sets, $\mathcal{M}_1$ and $\mathcal{M}_2$, where the requested rates $R_m$ and $R_m'$ of SUs in $\mathcal{M}_1$ and $\mathcal{M}_2$ satisfy $R_m' < R_m$. The proposed two-stage matching game and repeated auction algorithm is as follows:

1. **Initialization:** Let $Q_k$, $\bar{Q}_k$, and $\hat{Q}_k$ be the SUs quota and its upper and lower limits, respectively, for SBS $k$.
2. **Matching Stage:**
   a. SBS $k$ offers a number of channels $|\mathcal{C}_k|$ to SUs.
   b. Each SU $m$ with $R_m \leq Q_k$ is matched with SBS $k$.
   c. If $R_m > Q_k$, then SBS $k$ is required to adjust its offer $|\mathcal{C}_k|$ to accommodate SU $m$.
   d. If $|\mathcal{C}_k| > \bar{Q}_k$, then SBS $k$ is required to reduce its offer to $\hat{Q}_k$.
3. **Auction Stage:**
   a. Each SU $m$ with $R_m > Q_k$ participates in an auction to improve its utility.
   b. The auction is conducted using a sealed-bid auction with a symmetrically decreasing step size.
   c. The SU with the highest bid is selected, and the remaining SUs are discarded.
   d. The process is repeated until all SUs are matched.
4. **Final Assignment:**
   a. Each SU $m$ is assigned to SBS $k$ if $R_m' < R_m$.
   b. The remaining SUs are assigned to the next available SBS.

The proposed algorithm ensures that the primary communication is not affected, and the SUs are matched with the SBSs that can provide them with the required rates. The algorithm is simple and efficient, and it can be extended to accommodate more complex scenarios.
TABLE 2. Summary of possible errors during spectrum sensing

| SensingReality | ON | OFF |
|----------------|----|-----|
| **Correct detection:** $\theta_n(1 - p^\text{MD}_k)$ | SBS uses underlay power with MBS interference | SBS uses underlay power with no MBS interference |
| **Mis-detection:** $\theta_n p^\text{MD}_k$ | SBS uses full power with MBS interference | No false alarm: $(1 - \theta_n)(1 - p^\text{FA}_k)$ |

chosen from a range of quotas changing from $Q^\text{min}$ to $Q^\text{max}$, which corresponds to the different hardware limitations of each SBS. Both the SBSs and the SUs have different utility functions. In the proposed work, a many-to-one matching game is adopted as described in Section III-B.

A. SECONDARY USERS UTILITY

Depending on the operation of each SU, each user demands a minimum bit rate. The more data rate it gets from the SBS, the better. Each SBS assumes that it would be allocated a single channel and calculates the average data rate that can be achieved by the available channels to serve any SU. Therefore, the underlay power used by each SBS here is the minimum allowable underlay power over all channels, i.e.,

$$P_{u,k} = \min_{n \in N} (P_{u,k,n}).$$

(i) While using a macro channel $n$, the average rate from a SBS $k$ to any SU $m$ is

$$R_{m,k,n} = (1 - \theta_n)p^\text{FA}_{k,n} \log_2 \left[ 1 + \frac{P_{u,k}|h_{k,m}|^2}{\sigma^2} \right]$$

$$+ \theta_n(1 - p^\text{FA}_{k,n}) \log_2 \left[ 1 + \frac{P_{\text{MBS}}|h_{k,m}|^2}{\sigma^2} \right]$$

$$+ \theta_n p^\text{MD}_{k,n} \log_2 \left[ 1 + \frac{P_{\text{MBS}}|h_{k,m}|^2}{\sigma^2} \right],$$

(5)

where $p^\text{FA}_{k,n}$ and $p^\text{MD}_{k,n}$ are the probabilities of false alarm and mis-detection when SBS $k$ is sensing the operation over channel $n$, respectively. The channel gain between SBS $k$ and SU $m$, and that between the MBS using channel $n$ and SU $m$ are $|h_{k,m}|^2$ and $|h_{n,m}|^2$, respectively. $P_{\text{MBS}}$ is the transmission power of the MBS. The expression in (5) describes the possible four cases of the average bit rate from the MBS, summarized in Table 2. The first term describes the case when the MBS is OFF, and false alarm during the sensing phase occurs. In this case, the SBS transmits its signals with underlay power, and there is no macro interference on the secondary communication. The second term represents the case where the MBS is OFF, and no false alarm occurs. Hence, there is no macro interference, and the SBS uses maximum power. The third and fourth terms represent the cases when the MBS is ON. For the correct detection case, the SBS uses the underlay power to avoid causing intolerable interference on the MBS. However, MBS causes interference on that SBS, as in the third term. For the mis-detection occurs, SBS transmits with maximum power, and suffers from interference from MBS, as in the last term. (ii) While using a femto channel $f$, the rate becomes

$$R_{m,k,f} = (1 - \theta_f)(1 - p^\text{FA}_{k,f}) \log_2 \left[ 1 + \frac{P_{\text{MBS}}|h_{k,m}|^2}{\sigma^2} \right]$$

$$+ \theta_f p^\text{MD}_{k,f} \log_2 \left[ 1 + \frac{P_{\text{MBS}}|h_{k,m}|^2}{\sigma^2} \right],$$

(6)

where $p^\text{FA}_{k,f}$ and $p^\text{MD}_{k,f}$ are the probabilities of false alarm and mis-detection respectively when SBS $k$ is sensing FBS $f$. The transmission power of the FBS $f$ is $P_f$, the channel gain between SBS $k$ and SU $m$, and that between FBS $f$ and SU $m$ are $|h_{k,m}|^2$ and $|h_{f,m}|^2$, respectively.

Unlike the MBS channels, the femto channels are only accessed whenever the FBSs are not using them, due to the intolerable interference from SUs. In expression (6), the first term describes the case in which the FBS is OFF, and no false alarm probability is produced during sensing. Hence, the SBS transmits with its maximum power. The other possible case is when the FBS is ON, but the SBS fails to detect it. In that case, the SBS uses the channels and suffers from FBS interference.

To calculate the average rate from the different types of channels, the expression in (5) is multiplied by the probability of choosing one of the macro channels, which is equal to the number of macro channels per MBS over the total number of macro and femto channels, and that in (6) is multiplied by probability of choosing one of the FBSs to use its channel, which is equal to the number of channels per FBS over the total number of channels. Since there are multiple FBSs, the rate from (6) is summed over all the FBSs in the network. The resultant expression is the average rate for SBS $k$. To find that promised by the SBS $k$ to SU $m$, assuming TDMA, the average rate is divided by its number of users, whose maximum number is the quota of that SBS, as follows

$$R_{m,k} = \frac{1}{Q_k} \left( \frac{N}{(N + F)} R_{m,k,n} + \sum_{f=1}^{F} \left( \frac{1}{(N + F)} R_{m,k,f} \right) \right),$$

(7)

where $N$ is the number of macro channels, and $F$ is the number of FBSs. Accordingly, the SUs utility is the difference between the average promised rate by an SBS to it and the required rate by that SU, as follows

$$U_{m,k,\text{match}} = R_{m,k} - R_m,$$

(8)

where $R_m$ is the average required bit rate by SU $m$.  

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B. SECONDARY BASE STATIONS UTILITY

Since the goal of SBSs is to benefit the SUs without harming the PBSs communication, its utility is the average power received at the SU compared with the best average received power from any other SBS, considering the different sensing cases mentioned in Table 2. Hence, the utility differs for the macro channels and the femto channels as follows

(i) For the macro channels

\[ U_{m,k,n}^{\text{SBS,match}} = \theta_n (1 - p_{MD}^{m,k,n}) \max_{k' \neq k} \left( P_{u,k} | h_{k,m} |^2 \right) + (1 - \theta_n) (1 - p_{FA}^{m,k,n}) \max_{k' \neq k} \left( P_{\text{max}} | h_{k',m} |^2 \right) + \theta_n p_{MD}^{m,k,n} P_{\text{max}} | h_{k,m} |^2 \max_{k' \neq k} \left( P_{\text{max}} | h_{k',m} |^2 \right) + (1 - \theta_n) p_{FA}^{m,k,n} \max_{k' \neq k} \left( P_{u,k} | h_{k,m} |^2 \right). \]  

(ii) For the femto channels

\[ U_{m,k,f}^{\text{SBS,match}} = (1 - \theta_f) (1 - p_{FA}^{m,k,f}) \max_{k' \neq k} \left( P_{\text{max}} | h_{k,m} |^2 \right) + \theta_f p_{FA}^{m,k,f} \max_{k' \neq k} \left( P_{\text{max}} | h_{k',m} |^2 \right). \]

Similar to the SUs utility, (9) is multiplied by the probability of choosing one of the MBS channels, and (10) is multiplied by the probability of choosing that FBS and summed over all available FBSs in the network, as

\[ U_{m,k}^{\text{SBS,match}} = NU_{m,k,n}^{\text{SBS,match}} \frac{(N + F)}{(N + F)} + \sum_{f=1}^{F} U_{m,k,f}^{\text{SBS,match}} \frac{(N + F)}{(N + F)}. \]  

C. MATCHING ALGORITHM

Secondary Users Admission Algorithm

Input: \( U_{m,k,n}^{\text{SUS,match}}, U_{m,k}^{\text{SBS,match}} \), and \( Q_k \).

Output: \( A_{\text{stable}} \).

1: Initialization: Initialize the proposing SUs set \( \mu \) containing all SUs, and the assignment matrix \( A \).

2: SUs and SBSs sort their utilities in (8) and (11) in a descending order to form the preference lists.

3: while \( \mu \neq \emptyset \) do

4: for \( SU \ m \in \mu \) do

5: \( SU \ m \) proposes to the first SBS in its preference list.

6: if That SBS is matched to its quoted number of SUs then

7: \( SBS \) keeps the best \( Q_k \) SUs and rejects the worst \( SU \).

8: if \( SU \ m \) is chosen then

9: Remove \( m \) from \( \mu \).

10: Return the worst \( SU \) to \( \mu \).

11: Update the assignment set \( A \).

12: end if

13: else if That SBS is under-subscribed then

14: Remove \( m \) from \( \mu \) and match it with that SBS.

15: Update the assignment set \( A \).

16: end if

17: end for

18: end while

19: \( A_{\text{stable}} = A \).

The users admission is modeled as a college admission problem, where multiple SUs are assigned to a single SBS according to its quota. Each of the SUs and the SBSs have different utilities, as described in Sections III-A, and III-B, respectively, based on which they build their preferences. A stable matching algorithm, proposed in [32], is adopted to the considered problem. Algorithm III-C describes the case where SUs propose to the SBSs and the SBSs decides whether to accept or reject their proposals. The algorithm terminates with an SU weak pareto-optimal stable matching, when all the matching pairs are individually rational and no blocking occurs [29]. An optimal stable matching point for SBSs can be obtained due to an SBS-oriented matching. An SBS-oriented matching starts by SBSs and SUs creating their preferences lists, similar to Algorithm III-C. Then, SBSs propose to their most preferred SUs, and the SUs accept or reject their proposals where, the proposals made by a certain SBS \( k \) depends on its quota \( Q_k \).

IV. CHANNELS ALLOCATION GAME

Upon applying the first stage in the framework, namely, matching the SUs to different cognitive base station, we can represent this matching outcome by the set \( X_k = \{1, 2, \ldots, x_k, \ldots, X_k\} \), where \( 1 \leq X_k \leq Q_k \). \( X_k \) defines the number of SUs associated with the secondary base station \( k \). Assuming TDMA, the required rate for any of the SBSs in the channels allocation stage is the maximum required rate of any of its users multiplied by the number of time slots per each SBS. The number of time slots of a certain SBS is equal to the number of users assigned to it after the matching stage. Thus, the required rate is defined as

\[ \overline{R}_k = X_k \max_{1 \leq x_k \leq X_k} R_{x_k}. \]  

Each SUs required rate is assumed to be the minimum rate to allow for its communication. Therefore, with the SBS unifying the required rate for the associated SUs to be the maximum of all these minimum rates, some associated SUs can enjoy rates higher than their requested minimum. Nevertheless, this extra rate can be used by the individual SUs to improve their communication performance, e.g. use higher order modulation to communicate with improved quality of experience. A group of channels is given to each SBS, such that its users’ requirements are satisfied. A modified English auction is proposed to allocate primary channels to the secondary system, where the primary channels are considered the goods to be traded, the SBSs are the bidders, endowed with a monetary budget, and finally, the PBSs are the owners of the goods.
A. SECONDARY BASE STATIONS UTILITY

In this stage, the utility of SBS is the average achievable bit rate from any channel. This rate depends on the channel gain between the SBS and its associated SU, as well as the channel owner, either MBS or FBS. To define the utility, we start by defining the rates from different PBSs, as follows:

(i) considering the MBS channels,

\[ R_{k,n}^{SBS|x_k} = (1 - \theta_n)p_{k,n}^{FA} \log_2 \left( 1 + \frac{P_{u,k,n}|h_{k,x_k}|^2}{\sigma^2} \right) + \theta_n p_{k,n}^{MD} \log_2 \left( 1 + \frac{P_{max}|h_{k,x_k}|^2}{\sigma^2 + P_{MBS}|h_{k,x_k}|^2} \right) + \theta_n p_{k,n}^{MD} \log_2 \left( 1 + \frac{P_{max}|h_{k,x_k}|^2}{\sigma^2 + P_{MBS}|h_{k,x_k}|^2} \right). \]  

(ii) considering the FBS channels,

\[ R_{k,f}^{SBS|x_k} = (1 - \theta_f)(1 - p_{k,f}^{FA}) \log_2 \left( 1 + \frac{P_{max}|h_{k,x_k}|^2}{\sigma^2} \right) + \theta_f p_{k,f}^{MD} \log_2 \left( 1 + \frac{P_{max}|h_{k,x_k}|^2}{\sigma^2 + P_{MBS}|h_{k,x_k}|^2} \right) + \theta_f p_{k,f}^{MD} \log_2 \left( 1 + \frac{P_{max}|h_{k,x_k}|^2}{\sigma^2 + P_{MBS}|h_{k,x_k}|^2} \right). \]  

For simplicity, the worst cases corresponding to the SUs with least data rates are to be considered. This is done by taking the minimum value of the previous expressions over all SUs assigned to the same SBS, as

\[ U_{k,n}^{SBS,auction} = \min_{1 \leq x_k \leq X_k} R_{k,n}^{SBS|x_k}, \]  

\[ U_{k,f}^{SBS,auction} = \min_{1 \leq x_k \leq X_k} R_{k,f}^{SBS|x_k}. \]  

The expressions in (15) and (16) are combined to denote the final SBS utility in the auctions \( U_{k,n}^{SBS,auction} \) and \( U_{k,f}^{SBS,auction} \). We calculate the maximum number of channels demanded by a certain SBS by arranging the set of channels ascendingly according to the rate they give to the SBS. Then, we compare the required rate with the rate that the first channel could supply. If it is not enough, the required rate is compared to the rate that the first channel could supply, and so on, until reaching a rate equal to or more than that required by this SBS. \( Q_{k}^{ch} \) is the maximum number of channels demanded by SBS k.

B. PRIMARY BASE STATIONS UTILITY

The allocation of primary channels to the SBSs limits the PBSs communication. Therefore, the PBSs utility considers the interference of SBS caused on them and the degradation in data rate during their operation. The MBS and the FBS utility functions \( U_{k,n}^{MBS,auction} \) and \( U_{k,c}^{FBS,auction} \) are respectively formulated as

\[ U_{k,n}^{MBS,auction} = \theta_n (1 - p_{k,n}^{MD}) \log_2 \left( 1 + \frac{P_{MBS}|h_{k,n,i}|^2}{\sigma^2 + P_{u,k,n}|h_{k,n,i}|^2} \right) + \theta_n p_{k,n}^{MD} \log_2 \left( 1 + \frac{P_{MBS}|h_{k,n,i}|^2}{\sigma^2 + P_{max}|h_{k,n,i}|^2} \right). \]  

\[ U_{k,f}^{FBS,auction} = \theta_f (1 - p_{k,f}^{MD}) \log_2 \left( 1 + \frac{P_{MBS}|h_{k,j,i}|^2}{\sigma^2} \right) + \theta_f p_{k,f}^{MD} \log_2 \left( 1 + \frac{P_{h,j,i}^2}{\sigma^2 + P_{max}|h_{k,j}|^2} \right), \]  

where \(|h_{n,i,n}|^2\) and \(|h_{f,j,i}|^2\) are the gains of the channels between the MBS and its user i, and FBS f and its user j, respectively. \(|h_{k,n,i}|^2\) and \(|h_{k,j}|^2\) are the interference channels between SBS k and the MPU i using channel n, and between the SBS k and FPU j, respectively.

C. CHANNELS ALLOCATION ALGORITHM

Repeted English Auction channels allocation

Input: \( U_{k,n}^{joint}, Q_{k}^{ch} \) and \( \alpha \).

Output: \( A_{auctions} \).

1. Initializing: Set of unsatisfied SBSs, \( S = K, i.e. all SBS \) in the system; set of unallocated macro channels, \( C_{macro} = N, i.e. the set of all MBS channels in the system; and set of unallocated femto channels, \( C_{femto} = F \), i.e. the set of all FBS channels.

2. While \( (S \neq \emptyset) \) or \( (C_{macro} \cap C_{femto} \neq \emptyset) \) do

3. Initializing: \( p_{n+f}^{MD} \) a small value \( \epsilon \) where \( 1 \leq n \leq C_{macro}, \) and \( 1 \leq f \leq C_{macro}; D_{k}^{(0)} = \emptyset, \) where \( 1 \leq k \leq S; D_{ex}^{(0)} = \emptyset; \) \( \alpha = 0; \)

4. Repeat

5. Stage I: Demand sets calculation \( D_{k}^{(count)} \)

6. Each SBS k calculates \( M_{k,n+f}^{(count)} \) as in (20).

7. Each SBS k sorts its \( M_{k,n+f}^{(count)} \) descendingly to get \( \pi_{k,n+f} \).

8. Each SBS k creates its \( D_{k}^{(count)} \) as the macro or femto channels corresponding to the first \( Q_{k}^{ch} \) elements in \( \pi_{k,n+f} \).

9. Stage II: Excess demand sets calculation \( D_{ex}^{(count)} \)

for \( i = \{ 1, 2, \ldots, C_{macro} + C_{femto} \} \) do

for \( t = \{ 1, 2, \ldots, S \} \) do

if resource \( i \in D_{k}^{(count)} \cap D_{ex}^{(count)} \) then

\( D_{ex}^{(count)} = D_{ex}^{(count)} \cap \{ i \} \)

end if

end for

end for

Stage III: Walrasian Equilibrium Implementation

18. Each SBS k updates the prices as \( p_{n+f}^{(count+1)} = p_{n+f}^{(count)} + \alpha \delta(p_{n+f}^{(count)}) \)

where \( \delta(p_{n+f}^{(count)}) = \begin{cases} 1, & i \in D_{ex}^{(count)}; \\ 0, & \text{otherwise}. \end{cases} \)

19. \( \text{count} = \text{count} + 1 \)

20. Until \( D_{ex}^{(count)} = \emptyset \)

21. Update \( A_{auctions} \) with the allocation of channels over SBSs during this auctions round.

22. Calculate the new S as the set of unsatisfied SBSs, and the new \( C_{macro} \) and \( C_{femto} \) as the sets of unallocated

23. Update \( A_{auctions} \) with the allocation of channels over SBSs during this auctions round.

24. Calculate the new S as the set of unsatisfied SBSs, and the new \( C_{macro} \) and \( C_{femto} \) as the sets of unallocated
macro and femto channels after this auctions round.

25: end while

In this section, combinatorial auction theory is used to model the channels allocation problem. SBSs communicate with each other and implement the algorithm locally to find the best channels allocation mechanism in a distributed manner. Taking into consideration both the primary and secondary systems, the utility function is assumed to be the weighted sum of the SBSs utility in (15), and (16), and that of the primary base station described in (17), and (18).

\[ U_{k,n+f}^{\text{joint}} = \lambda U_{k,n+f}^{\text{SBS,auction}} + (1 - \lambda) U_{k,n+f}^{\text{PBS,auction}}, \]  

where \(\lambda\) is the weighting parameter by which we could increase the priority of one of the utilities over the other. \(U_{k,n+f}^{\text{SBS,auction}}\) and \(U_{k,n+f}^{\text{PBS,auction}}\) are the utilities of the SBSs while using either the MBS channels or the FBSs channels, and that of PBSs, respectively. Following [29], a modified English Auction is implemented. The primary channels; macro and femto channels, are the goods to be traded, the MBSs and the FBSs are the owners, and the SBSs are the consumers. Initially, the SBSs are endowed with a monetary gain \(M_{k,n+f}^{(0)}\), which is the joint utility \(U_{k,n+f}^{\text{joint}}\), difference the initial channels prices \(p_{n+f}^{(0)}\), as follows

\[ M_{k,n+f}^{(0)} = U_{k,n+f}^{\text{joint}} - p_{n+f}^{(0)}. \]  

The price of a channel is increased by a certain value \(\alpha\) if multiple SBSs demand this channel at the same time. Accordingly the monetary gain \(M_{k,n+f}^{(0)}\) is updated each loop.

Algorithm IV-C describes the proposed mechanism. The algorithm contains two main loops; an inner loop for a single auction, and an outer loop for repeating the auctions. The inner loop is divided into three stages starting from lines 3 till line 22, as follows

i Calculation of demand sets for each SBS \(\mathcal{D}_k\), which contain the channels required by SBS \(k\) to serve its associated SUs. Each SBS sorts its monetary gain in a descending order and saves the channels corresponding to the highest monetary gain in the set \(\mathcal{D}_k\). The number of channels saved in \(\mathcal{D}_k\) of each SBS \(k\) is equal to \(Q_{\text{ch}}\).

ii Based on the demand sets of all the SBSs, the excess demand set \(\mathcal{D}_{\text{ex}}\) is evaluated. \(\mathcal{D}_{\text{ex}}\) contains all the channels demanded by more than one SBSs.

iii In order to reach Walrasian equilibrium, the prices of the channels in the excess demand set are increased by \(\alpha\). Hence, in the next loop, fewer SBSs demand the channels in \(\mathcal{D}_{\text{ex}}\), and so on until only one SBS could afford each channel.

The previous three stages are repeated, in the inner loop, until each channel is affordable by only one SBS or not affordable by any. The allocation of channels over the SBSs is saved in \(A_{\text{auctions}}\), as in line 23. At this end, neither full occupancy of the channels nor full satisfaction of the SBSs is guaranteed to occur. Satisfaction of a SBS is defined by the satisfaction of all of its associated SUs. The outer loop is proposed to consider the two mentioned issues. In line 24, the unsatisfied SBSs and the unallocated channels from the previous round are saved in \(\mathcal{S}, C_{\text{macro}}, \) and \(C_{\text{femto}}\), respectively. The auction is repeated with the same prices incremental factor, \(\alpha\), while resetting the channels prices to a very small value \(\epsilon\), until either all the SBSs are satisfied or all the channels are allocated.

V. SIMULATION SETUP AND RESULTS

We simulate a 5G HetNet with a single MBS, having 6 macro channels and 18 FBSs, each having a single channel. The secondary system consists of 12 SBSs and 36 SUs. The transmission powers of the MBS, FBSs, and SBSs are 40W, 200mW, and 1W, respectively [35]. Each SBS could assign a random number of SUs that ranges from \(Q_{\text{min}} \leq Q_k \leq Q_{\text{max}}\), where \(Q_{\text{min}} = 2\) SUs per SBS, and \(Q_{\text{max}} = 5\) SUs per SBS. At each SBS, an energy detector is used to sense the available spectrum utilization, where \(p_{k,F}^{\text{FA}}\) and \(p_{k,F}^{\text{FA}}\) are fixed and equal to 0.05, and \(N_e\) is 20. The MBS, and FBSs are assumed to be idle for 25% of time [29]. The signal-to-noise ratio (SNR) is set to 0 dB for all the channels in the system.

A. ADMISSION STAGE ANALYSIS

A Many-to-One matching is used to model the SUs assignment to the SBSs in the first stage. The preferences of the SUs and the SBSs are described in Sections III-A and III-B.

Figure 2 illustrates the utility region between the SBSs and the SUs after the matching game. The utility region describes the relation between the SUs sum rates, and the SBSs utility sum. The maximum bound and the quoted bound are generated using the Hungarian method [36]. The maximum bound encloses all the possible SUs-SBSs matchings assuming the quota is infinite, while the quoted bound encloses all the SUs-SBSs matchings assuming the quotas \(Q_k\) of the SBSs are different and take values from 2 to 5. The figure shows that a bounded near optimal stable matching point exists upon
the SU-oriented matching due to Algorithm III-C. Simulation also proves that the SBS-oriented stable matching point coincides with that of the SU-oriented matching. Hence, the obtained point is optimal for both the SUs and SBSs.

In Figures 3, and 4, the number of MBS channels \((N)\) is set to \(2x\), that of FBSs \((F)\) is set to \(3x\), that of SBSs \((K)\) is set to \(2x\), and that of SUs \((M)\) is set to \(6x\), i.e., for \(x = 6\), \(N = 6, F = 18, K = 12,\) and \(M = 36\). Figure 3 studies the average number of proposals per SU in the SU-oriented matching approach in Algorithm III-C as the number of SUs increases. For \(Q_k = M\), i.e., any SBS could assign all the SUs in the system to itself, the average number of proposals made per SUs is equal to one. Since SBSs shall immediately accept any user proposing to it, due to its large quota. On the other hand, for a limited quota; \(2 \leq Q_k \leq 5\), the average number of proposals increases, since SBSs would only accept the best \(Q_k\) SUs based on their preferences lists. Moreover, the figure shows that the number of proposals increases with the increase in the number of SUs and the number of SBSs. This can be explained as the SUs are more likely to be rejected by a larger number of SBSs. In Figure 4, the average number of proposals per SBS in the SBS-oriented matching approach is investigated against increasing the number of SBSs. The average number of proposals made by each SBS is always greater than one as each SBS proposes to a number of SUs based on its quotas. For \(Q_k = M\), the average number of proposals per SBS increases, since the SBSs propose to a larger number of SUs. Figures 3 and 4 show that the matching game quickly converges to a stable point even for large numbers of SBSs and SUs.

### B. ALLOCATION STAGE ANALYSIS

After the matching of SUs to SBSs, where both the SU-oriented matching point and the SBS-oriented stable matching point coincide, giving the exact matching results, as demonstrated in Figure 2, a repeated Modified English auctions is introduced for the channels allocation over SBSs. In Figure 5, the utility region for the channels allocation game is plotted for \(\alpha = 0.01, \lambda = 0.5\) [29], [32]. It represents the relation between the SBSs sum rate and the PBSs sum rate after the channels allocation. The maximum and quoted bounds are generated using the Hungarian method [36]. The maximum bound represents the maximum sum rate that the SBSs and the PBSs can achieve through the channels allocation assuming no quota restrictions. While the quoted bound represents the possible sum rates assuming the SBSs have certain \(Q_{k}^{b}\). The figure shows that there exists a Walrasian equilibrium point for Algorithm IV-C, which is very close to the quoted bound.

In Figures 6 – 10, we compare between single auction and the proposed repeated auction in terms of SBSs sum rate, SBSs satisfaction, channels utilization, and average number of proposals, respectively, while varying the prices.
incrementing factor $\alpha$ from 0.01 to 0.1. Three different cases of system parameters are considered, as shown in Table 3.

It is proved that the proposed repeated auction algorithm outstands the single auction in [32] in different metrics.

In Figure 6, the SBSs sum rate after the channel allocation stage is studied versus $\alpha$ for the three cases considered. As a general trend, as $\alpha$ increases, the SBSs rate decreases for a single auction. However, the rate of SBSs is enhanced in repeated auctions compared to the single auction. This is justified by the fact that during single English auction, for a certain $\alpha$, whenever a channel is demanded by more than one SBS, its price is increased until only one or none SBS demands it. Thus, for larger $\alpha$, the channels are becoming more difficult to afford, that the best channels are left over and SBSs go for less preferable cheaper macro channels. At the end, the best most demanded channels are unallocated to any SBS, and an adequate number of SBSs are unsatisfied resulting in decreasing the sum rate. As $\alpha$ increases, more SBSs with limited monetary budget $M_{k,n+f}^{(\text{count})}$, defined in (20), are allocated channels with low data rates or even no channels. Hence, the SBSs rate decreases. However, repeating the auction while resetting the channels prices $p_{n+f}^{(\text{count})}$ to a small value $\epsilon$, gives the best most demanded channels and the SBS with limited monetary gain another chance. Since, only the unallocated channels and the unsatisfied SBS re-enter the auction. After multiple auction rounds, the SBSs sum rate is enhanced as shown in Figure 6. It is observed that as the number of SBSs increases, i.e., for $K = 24$ as in case III, the rate enhancement becomes more significant compared to cases I and II.

Figure 7 illustrates the average percentage of satisfied SBSs after the channels allocation stage during single auction and repeated auctions for the three study cases. An SBS is said to be satisfied, when all of its associated SUs achieve their minimum required data rate, by using the allocated primary channels to this SBS. In general, for a single auction, as $\alpha$ increases, the percentage of satisfied SBSs decreases. As mentioned earlier, this is due to the limited monetary budget of some SBSs, which are not able to afford the high prices of the channels. On the other hand, in repeated auctions, resetting the channels prices $p_{n+f}^{(\text{count})}$ to a small value $\epsilon$ causes the SBSs to be more satisfied in comparison to the single auction case. The SBSs are 100% satisfied only in case I, where the number of macro and femto channels are large enough. However in cases II and III, not all SBSs are satisfied since the number of channels is not sufficient to serve the SBSs requirements.

The impact of $\alpha$ on the average percentage of unused macro and femto channels are introduced in Figures 8, and 9, respectively. Unused channels are those not allocated to any SBS after the channels allocation stage. After a single auction, not all the primary channels are allocated to SBS, even if some SBS are still not satisfied. The percentage of unused primary channels, both macro and femto, increases as $\alpha$ increases during a single auction, while it is kept almost constant for repeated auctions. From these two figures, it is shown that SBSs prefer femto channels to macro channels. For case I, where all the SBSs are satisfied, a small percentage of the femto channels is unused, while a larger percentage of macro channels is unused. Similarly in cases II and III, where not all the SBSs are satisfied, a larger percentage of macro channels is unused compared to the femto channels. This is due to the fact that femto channels suffer from less primary interference, i.e., femto channels give higher data
rates to SBSs on average compared to macro channels. In Figure 10, the average number of proposals by any SBS to the primary channels, macro and femto channels, during single and repeated auctions in Algorithm IV-C is illustrated for the three study cases considered. The average number of proposals per SBS in repeated auction is higher than that in a single auction. However, the increase in proposals number is reflected in increasing data rate as shown in Figure 6, or enhancing SBS satisfaction percentage as shown in Figure 7. In addition, the repeated auctions achieve a better usage of available primary channels as shown in Figures 8 and 9. In general, the average number of proposals decreases as \( \alpha \) increases for a single auction. For repeated auctions, the average number of proposals decreases as \( \alpha \) increases until a certain value of \( \alpha \) that makes some SBSs unsatisfied while there are unused primary channels from a single auction round in the repeated auctions. At this value, and beyond, the number of proposals increases due to the proposals made in the next auction rounds. The difference between the single and repeated auction becomes remarkable as the number of SBSs increases as in case III, compared to cases I and II. However, this improves the data rate and satisfaction percentage and channels usage as explained in Figures 6 – 9. If the available channels in the system are insufficient, the average number of proposals per SBS is increased as in case II, compared to case I.

The number of auction rounds versus \( \alpha \) due to Algorithm IV-C is illustrated in Figure 11 for the three study cases. Varying \( \alpha \) from 0.01 to 0.1 causes the number of auctions to increase. It is noted that if there is an insufficient number of channels, the number of repeated auction rounds is increased as in case II compared to case I. Also, if the number of SBS
is increased, the number of rounds increases, as in case III. The effect of varying the system parameters on the system performance could be summarized as follows
Case I: For a small number of SBSs and SU, and a large number of macro and femto channels, in a single auction not all the SBSs are satisfied, although there are enough channels. In repeated auctions, all the SBSs are satisfied and most of the femto channels are allocated while a larger percentage of macro channels are unused. However, the average number of proposals for repeated auctions is larger than that for a single auction.
Case II: For a small number of SBSs and SU, and a small number of primary channels, some SBS are not satisfied in both single and repeated auctions, but the macro and femto channels are almost 100% used in the repeated auction.
Case III: When the number of SBSs is very large, the repeated auctions become more significant compared to a single auction. SBSs rate is greatly enhanced, at the expense of a larger number of proposals.

In figures 10-9, we compare between the single auction in [32], and the proposed repeated auction, while changing the prices incrementing factor during Algorithm IV-C. In Figure 10, it is shown that the average number of proposals in the single auction and the repeated auctions are nearly the same for small values of prices incrementing factor \( \alpha \). For larger values of \( \alpha \), the average number of proposals in a single auction decreases, since it becomes harder to afford some of the channels, as their prices raise abruptly. Repeating the auction while resetting the prices to a very small value each round, more SBSs are able to afford the unallocated channels in the successive rounds. Hence, the curve starts increasing again after a certain \( \alpha \) equals to 0.04 approximately. For the same reason, in Figure 6 the SBSs rate decreases as \( \alpha \) increases. However, the slope of the increased loss in the rate is reduced significantly in repeated auctions compared to the single auction.

In Figure 7, the percentage of satisfied SBSs after the users admission and the channels allocation stages is illustrated. In general, as \( \alpha \) increases, the percentage of satisfied SBSs decreases in a single auction. For repeated auctions, the percentage of satisfied SBSs is fixed at 100% if the number of available channels in the system is large enough to satisfy all the requirements of the SBSs. For \( M = 30, K = 10, N = 10, F = 4 \), there are plenty of channels for serving the SBSs, thus 100% satisfaction is achieved in Fig 7 while not all the macro and femto channels are used as illustrated in Figure 8, and 9. For a fewer number of primary channels, \( N = 10 \) and \( F = 2 \), or a larger number of SU and SBS, \( M = 60, K = 20 \), the SBSs are not completely satisfied neither in single auction nor in repeated auction. Yet repeated auctions improves the satisfaction percentage of the SBSs in both cases. Also in Figure 8, and 9, for a fewer number of primary channels, \( N = 10 \) and \( F = 2 \), or a larger number of SU and SBS, \( M = 60, K = 20 \), in the repeated auctions, all the macro and femto channels are used, unlike the case of a single auction. In case where there are plenty of channels to satisfy the SBSs requirements, SBSs prefer to have the femto channels; the unused macro channels percentage in a repeated auctions for \( M = 30, K = 10, N = 10, F = 4, \) and \( \alpha = 0.01 \) is around 38%, while that of femto channels is around 1.1%.

Figure 12, and Figure 13 describe the convergence of auctions as the number of SBSs increases. The numbers of FBSs, MBS channels, SBSs, and SU are related as follows, \( F : N : K : M = 1 : 2 : 3 : 8 \), where the number of SBS ranges from 0 to 120, and the prices incrementing factor is fixed at 0.01. In Figure 12, the average number of proposals per SBS till convergence of Algorithm IV-C is studied against the number of SBSs. As the number of SBSs increases, the average number of proposals by any SBS increases during a single auction or repeated auctions. The average rate per SBS after the channels auction is plotted in Figure 13. It is noticed that repeated auctions greatly enhance the rate of SBS as compared to the single auction for larger systems. As the number of SBSs increases, the average proposals number in repeated auctions exceeds that of single auction at the expense of enhancing the rate per SBS.

The size of the whole network is increased with the increase in the SBS, using the same ratio used to generate Figures 3, and 4.

The game-theoretic auction model and the matching theory are compared by applying both approaches to the channels allocation problem. The distributed matching game in [29] is applied to the channels allocation problem considered in this work for the matching game approach. Figures. 14, 15, and 16 are presented to compare the performance of the two methods. To compare the proposed repeated auction with the matching-based channels allocation, the matching game preferences lists for the SBSs are depicted from the utility function in (15) when using a macro channel and (16) when using a femto channel. Similarly, the PBSs preferences lists
In Figure 14, the percentage of satisfied SBSs is plotted against increasing the number of SBSs. Figures 15, and 16 represent the average percentages of the unused macro and femto channels, respectively, versus the number of SBSs. Generally, a single auction game gives a weak performance in terms of SBSs satisfaction and usage of primary channels compared to matching game and repeated auctions game. The matching game gives lower satisfaction percentages of SBSs compared to the repeated auction. SBSs tend to be matched first to femto channels for channel usage, then to the macro channels. This performance explains the higher percentages of unused macro channels than the femto channels, where the difference between them reaches around 72% at $K = 40$ SBSs. Unlike this, in the repeated auctions, the difference between the unused macro channels percentage and that of the femto channels is around 41% at $K = 40$ SBSs. Hence, the repeated auction game balances the load between the macro and femto channels, i.e., decreasing the harm caused to femto channels and giving more opportunity to the macro channels to be allocated to SBSs. This behavior is due to the pricing of the primary channels in the auction, where femto channels with high demand is assigned higher prices, and fewer SBSs are able to afford them, compared the macro channels in terms of SBSs satisfaction and usage of primary channels.

FIGURE 15. Average percentage of unused macro channels after channels allocation, using a matching game, a single auction and a repeated auction, versus number of SBSs.

FIGURE 16. Average percentage of unused femto channels after channels allocation, using a matching game, a single auction and a repeated auction, versus number of SBSs.
channels with the lower prices.

One more point to consider is that at low numbers of SBSs, i.e., at $K = 2$, the available number of channels is deficient in serving the SBSs requirements. This deficiency is translated into the relatively low satisfaction percentage plus the low unused macro and femto channels percentages. At this point, the performance of the matching algorithm and the repeated auction is comparable.

VI. CONCLUSION

The problems of SUs assignment, and channels allocation in 5G HetNets are investigated in this paper. The paper considers practical situation where primary channels have different natures, i.e. macro-cell channels with existing primary transmission, and macro channels with the primary user absent as well as femto channels with restricted use when the femto transmission is suspended and having a higher price than the macro-channels. A college admission many-to-one matching game is used to match between SUs and their associated SUs. Simulation results show the existence of a Walrasian equilibrium point and that a 100% satisfaction of the SBSs requirements is achievable compared to a single auction and a many-to-one matching algorithm for a large number of channels. Moreover, repeated auctions allow for load balancing between the macro and femto channels allocated to SBSs.

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