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# Spectrum-Efficient QoS-Aware Resource Assignment for FFR-Based D2D-Enabled Heterogeneous Networks

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**ABSTRACT** Small cells and Device-to-Device (D2D) communication can improve the coverage and capacity of cellular systems, thereby enabling an enriched customer experience. To optimize that experience, this paper considers a problem of uplink weighted sum rate maximization for a single cell heterogeneous network containing macro cellular users, D2D users and femto-cell users. In particular, in order to control the co-tier and cross-tier interferences, a new Fractional Frequency Reuse (FFR) architecture is developed in which we seek to maximize a weighted sum rate, subject to minimum rate requirements and transmission power constraints. In order to tackle the resulting mixed integer nonlinear optimization problem, we develop a decomposition-based strategy. The proposed strategy solves the admission control, power control, and matching subproblems optimally, and allocates the remaining free sub-channels by using a heuristic suboptimal algorithm. Numerical results demonstrate that the proposed scheme, on average, achieves around 96% of the system sum rate of the optimal Branch and Bound method with much lower computational cost.

**INDEX TERMS** HetNet, femtocell, D2D, FFR, sum rate, transmission mode, optimization.

## I. INTRODUCTION

Heterogeneous Network (HetNet) and Device-to-Device (D2D) communication are promising techniques to improve the spectral efficiency of wireless communication networks [1]. In general, a HetNet consists of multiple tiers (or layers) of networks of different cell sizes/footprints and/or of multiple radio access technologies [2]. HetNets are an effective way to provide a higher system capacity, to improve network coverage, service quality and fairness, and to facilitate the integration of new types of networks, connectivity, and applications [3].

D2D communication is defined as direct communication between two mobile users without passing through the Base Station (BS) or core network. D2D communication enables the network to exploit the large channel gains between nearby devices to reduce power consumption and interference, and hence it facilitates spectral reuse. Inband D2D communication may use the cellular spectrum in common with the cellular users (reuse mode), or, use part of the cellular spectrum

separately (dedicated mode) [4]–[6]. However, underlay reuse techniques are more attractive in communication networks because of the limited available frequency spectrum, and thus co-tier and cross-tier interference is inevitable [7].

Fractional Frequency Reuse (FFR) is an interference avoidance technique that seeks to reduce co-tier/cross-tier interference with minimal cooperation among the BSs [8]. In addition to interference avoidance mechanisms (such as FFR schemes), interference coordination strategies are needed to assign the optimal transmission power and Sub-Channels (SCHs) to the users while guaranteeing their Quality of Service (QoS) requirements. (In a multicarrier-based system, each SCH would typically consist of a block of subcarriers, i.e., a “resource block”.)

To place the approach that will be proposed in this paper in context, we observe that there has been some research work addressing capacity improvement in D2D-enabled heterogeneous cellular networks. With the aim of maximizing D2D capacity, a density analysis and power allocation for D2D users (DUs) was performed in [9]. The original problem was decomposed into two sub-problems. The power allocation sub-problem was solved by the Lagrangian method,

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and it was proved that the optimal solution for the DU density sub-problem exists in a fixed interval. Finally, a linear searching method was proposed to find the optimal density and power allocation of D2D transmission with the target of capacity maximization over multiple bands. In [10], the problem of mode selection, resource allocation and interference management with the aim of maximizing the profit of DUs was formulated provided that the interference perceived by the cellular communication is controlled. The formulated problem was solved through a learning structure based on the Markov approximation. The authors in [11] formulated the throughput maximization problem for D2D communication underlying cellular networks which is NP-hard. They developed an algorithm based on an interference-aware partitioning scheme in order to solve the problem. In order to maximize throughput of D2D links in an uplink network scenario, the authors in [12] investigated a joint problem of mode selection and resource allocation considering an energy harvesting constraint and the QoS of cellular users (CUs). In [13], the authors aimed to maximize network throughput subject to the constraints related to user performance, fairness, mode selection (cellular or D2D), transmission power, and energy harvesting techniques. In order to improve throughput of D2D multicasting system on dedicated spectrum resources, and ensure fairness among the CUs, in [14], a weighted utilitarian bargaining solution was utilized. The presence of small cells was not considered in the network scenarios of those works. The authors in [15] formulated the problem of optimizing the power and density of small BSs, and the spectrum fraction allocated to DUs, with the goal of maximizing the D2D communication throughput for critical conditions. In that work, neither the QoS requirements of the users were considered, nor the appropriate solution strategy for the formulated problem was presented. A leader-follower utility maximization problem for a heterogeneous macrocell/femtocell network was considered in [16], where the power allocation problem for D2D communications was formulated as a Stackelberg game. However, channel assignment was not performed for the D2D users. In order to manage interference in a heterogeneous network, the authors in [17] proposed a distributed algorithm based on the matching theory, which assigns cellular resources to D2D communications. The problem of throughput maximization for a two-tier cellular network was considered in [18]. To that end, three different transmission modes including cellular, reuse and dedicated modes were considered for the users. User transmission modes were determined based on two traffic-aware algorithms. The efficiency of that approach was not studied in the presence of small cells.

FFR schemes are commonly used for interference control in cellular networks. However, in most cases they are inter-cell FFR schemes, which do not consider the existence of both the small cells and D2D devices in the network. The capacity maximization problem for Femto-cell Users (FUs) was solved in [19] through a joint channel allocation, mode selection and power control scheme for CUs and DUs in femtocells. A simple FFR scheme was also used to reduce the

cross-tier interference. However, that FFR scheme could not handle the co-tier interference between the femtocells. Furthermore, SCH reuse was not considered for potential DUs, since pre-determined dedicated SCHs were assigned to them. In that work, CUs located in the center zone of the macro-cell were treated as primary users, with each of them being assigned an orthogonal SCH. The authors in [20] considered a D2D network capacity maximization problem subject to QoS requirements and power constraints. They also proposed an FFR scheme in order to reduce the co-tier interference between the neighboring macrocells. By decoupling the problem, a suboptimal solution was proposed to assign available resource blocks to the users. However, the power assignment was fixed and it did not consider the QoS requirements for the DUs and FUs. The authors in [21] investigated joint user association and multi-cell resource allocation using an FFR framework for spectrum sharing among cells in heterogeneous networks. Resource partitioning was considered among multiple reuse patterns and the problem of multi-cell multi-user channel assignment together with user association optimization was formulated. They proposed sparse algorithms to find the optimal solution. The authors in [22] proposed a distance-based resource allocation for D2D communication with an FFR mechanism to reduce the interference. In their FFR scheme, both the cell inner and outer regions are partitioned into three equally dimensional sectors. Each cell in a sector can access the whole frequency band using directional antennas. Although that method improves the system performance and spectral efficiency, it ignores the interference between DUs and CUs and does not analyze the presence of small cells in the network. The authors in [23] proposed FFR structures with directional antennas for DUs, FUs, and CUs to reduce the cross-tier interference. Their proposed FFR allocates resources to each tier orthogonally in each region. They presented resource allocation algorithms to maximize energy efficiency of DUs and spectral efficiency of FUs. The authors in [24] proposed spectrum allocation and spectrum sharing schemes to suppress the interference in a D2D-enabled cellular network. They assumed that each BS has an exclusion region, and D2D links can be established outside the exclusion regions. CUs are classified into central users and the remaining edge users. A fraction of the total bandwidth is shared among the DUs and central CUs, and the remaining spectrum is utilized by the edge CUs. In [25], a new FFR scheme was provided considering the case of coexisting small cells and macrocells, where the total frequency-band allocations for different macrocells were decided based on the traffic intensity and the traffic classification in terms of real-time and non-real-time traffic. D2D communication was not considered in the network model of that work. The authors in [26] and [27] proposed cross-cell FFR-based frequency resource allocation schemes. However, they did not consider presence of the small cells in the network model. Comparison of the related work is summarized in Table 1.

In this paper, we consider a three-tier HetNet with one macrocell serving cellular users, femtocells serving local

TABLE 1. Comparison of related work.

Ref.	Objective of the maximization problem	FFR	D2D power control	D2D spectrum allocation	Small cell Power allocation	Small cell spectrum allocation	QoS	Mode selection
[9]	Capacity of DUs	×	✓	×	×	×	AU	×
[10]	Profit of DUs	×	×	✓	×	×	CUs	✓
[11]	Throughput of DUs	×	×	✓	×	×	AU	×
[12]	Throughput of DUs	×	✓	✓	×	×	CUs	✓
[13]	Overall system throughput	×	✓	×	×	×	AU	✓
[14]	Pay-off of BS	×	×	✓	×	×	×	×
[15]	Throughput of DUs	×	×	✓	✓	×	×	×
[16]	Utility of users	×	✓	×	×	×	×	×
[17]	Product of rate and coverage probability	×	×	✓	×	✓	AU	×
[18]	Overall system throughput	×	✓	✓	×	×	AU	✓
[19]	Throughput of FUs and DUs	✓	✓	✓	✓	✓	AU	✓
[20]	Sum rate of DUs	✓	×	✓	×	✓	CUs	×
[21]	Average user rate	✓	×	×	×	✓	×	×
[22]	Overall system throughput	✓	✓	✓	×	×	AU	×
[23]	EE of DUs and SE of FUs and CUs	✓	✓	✓	✓	✓	AU	×
[24]	×	✓	×	✓	×	×	AU	×
[25]	×	✓	×	×	✓	✓	×	×
[26]	×	✓	✓	×	×	×	AU	×
[27]	Overall system throughput	✓	×	✓	×	×	AU	×
Proposed scheme	Weighted sum rate of the system	✓	✓	✓	✓	✓	AU	✓

AU: All Users ✓:included ×: not included

users, and devices operating in D2D mode. A new FFR method is proposed, which reduces the cross-tier interference among the macrocell and femtocell users and prevents the co-tier interference among the femtocells. Also, with the objective of maximizing a weighted sum of the rates, we perform optimal admission control, power control, and matching for the users in the proposed network framework, sequentially. A heuristic SCH allocation algorithm is also proposed for assigning dedicated SCHs. A special feature of our work is that, there are no pre-assigned SCHs in the network. The available SCHs are assigned to the users, which acquire higher data rates regardless of being served by Femto Base Stations (FBS) or the Macro Base Station (MBS), and thus flexibility and selectivity in the network is increased. In addition, the proposed algorithm determines, implicitly, whether it is better for the network to support a given communication link in reuse mode or dedicated mode, depending on the network conditions. In reuse mode, users can operate on the same SCH but must manage the interference they cause to each other, whereas in dedicated mode the use of that SCH is restricted to one user.

The rest of the paper is organized as follows: Section II describes model of the system. The problem of weighted sum rate maximization is formulated in Section III. The proposed algorithms for solving the problem are presented

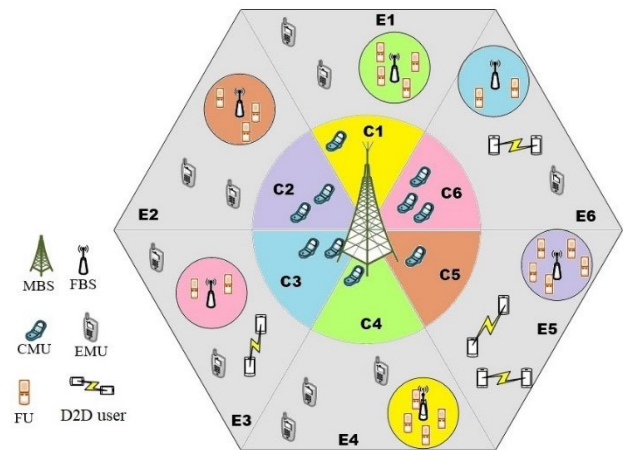


FIGURE 1. System model with the proposed FFR deployment for  $M = 6$ .

in Section IV. In Section V, the performance of the proposed approach is evaluated through the complexity analysis and simulations. Finally, the paper is concluded in Section VI.

II. SYSTEM MODEL

Fig. 1 illustrates the system model for the proposed FFR deployment. We consider the uplink of a three-tier macro/femto/D2D network in a single cell system with macro

users in the center zone of the cell, and macro, femto and D2D users in the edge zone. In the proposed FFR scheme, each zone (center and edge) is partitioned into  $M$  equal sectors, where  $M$  is an even number. A femtocell is provided in each sector in the edge zone, although its location is random. Each femtocell, represented by  $f_m$ , is available to serve users in its coverage area. It is assumed that the femtocells are configured in closed access mode, in which only approved users can use the femtocell. In addition, the system frequency bandwidth  $B$  (comprising  $N$  sub-channels) is separated into two non-overlapping sets of SCHs  $\mathcal{B}_C$  (comprising  $N_C$  sub-channels) and  $\mathcal{B}_E$  (comprising  $N_E$  sub-channels), where the SCHs in  $\mathcal{B}_C$  are assigned to the center zone macro users (CMUs) and the FUs in the edge zone, while the SCHs in  $\mathcal{B}_E$  are allocated to the edge zone macro users (EMUs) and the DUs. Furthermore,  $\mathcal{B}_C$  is divided into  $M$  equal sets of SCHs,  $\mathcal{B}_{C_1}, \dots, \mathcal{B}_{C_M}$ , each of which is allocated to the CMUs located in corresponding sectors of the center zone  $C_1, \dots, C_M$  (represented by different colors in Fig. 1). The sets  $\mathcal{B}_{C_m}$  will be called subbands. FUs occupy the SCHs in  $\mathcal{B}_C$  according to their locations in the sectors of the edge zone ( $E_1, \dots, E_M$ ) as illustrated in Fig. 1, where users located in the areas with the same colors, use the same set of SCHs. Therefore, the set of allocated SCHs for the  $m$ th femtocell ( $f_m$ ) located in sector  $E_m$  is defined as  $\mathcal{B}_{f_m} = \mathcal{B}_{C_i}$ , where:

$$i = \begin{cases} m + \frac{M}{2} & 1 \leq m \leq \frac{M}{2}, \\ m - \frac{M}{2} & m > \frac{M}{2}. \end{cases} \quad (1)$$

The frequency reuse factor for the EMUs and DUs is 1, and hence in the edge zone cellular users share the frequency resources with DUs. The proposed FFR method prevents co-tier interference among femtocells while reducing the cross-tier interference between FUs and CMUs.

As the distance from the CMUs to the MBS is comparatively short, it is assumed that they work only in cellular transmission mode. It is assumed that the number of active CMUs in each sector of the center zone is smaller than or equal to the number of SCHs allocated to that sector. Similarly, the number of active EMUs in the edge zone is smaller than or equal to the number of SCHs allocated to the edge zone.

We suppose that each user occupies at most one uplink SCH. Also, each DU can share only one uplink SCH with a cellular EMU, and each FU can share only one uplink SCH with a cellular CMU. In other words, to avoid intense interference, no SCH in any subband is shared between cellular users, and the scenario where multiple DUs (FUs, respectively) share an SCH with an EMU (a CMU, respectively) is structurally avoided.

As the focus of the paper is on exploiting the adaptability of the D2D and femto users, the transmission power of EMUs and CMUs is assumed to be fixed. We consider a centralized network configuration, in which, mode selection,

power control, and SCH allocation of the users are performed at the MBS, and then related information is delivered to the users. The channel gain for each transceiver pair is assumed to be quasi-static (i.e., constant over the transmission duration), and all the channel state information is available at the MBS. Specifically, the MBS can be informed about the D2D channel state measurements through the information reported via physical uplink shared channel (PUSCH), random access channel (RACH), and etc., [28]. Also, there is a direct wire connection between the FBSs and the MBS to coordinate with each other. MBS computes the scheduling parameters of the FUs and broadcasts the values to all the FBSs through the high speed backhaul. To enable simple implementation, we assume that single user decoding is utilized at the receivers, in which interference is treated as noise.

Let us define  $h_u$  as the channel gain between transmitter  $u$  and its related receiver (MBS for cellular users, FBS for FUs, and D2D receiver for DUs), and  $g_{u'}$  as the interfering channel gain from transmitter  $u'$  on the common SCH. Let us also denote the Additive White Gaussian Noise (AWGN) power on each SCH by  $\sigma_0^2$ . Let  $P_u$  be the transmission power of FU  $u$ , and  $P_{\text{cmu}}$  be the transmission power of the CMUs. Then, the received signal-to-interference-plus-noise ratio (SINR) at each FBS for the transmission of its FU  $u$ , and at the MBS for the transmission of CMU  $u'$  on SCH  $n$ , are defined respectively as:

$$\Gamma_{u,n} = \begin{cases} \frac{P_u h_u}{\sum_{u'=1}^{|\mathcal{U}_{MC}|} x_{u',n} P_{\text{cmu}} g_{u'} + \sigma_0^2} & \forall u \in \mathcal{U}_F, u' \in \mathcal{U}_{MC} \\ \frac{P_{\text{cmu}} h_{u'}}{\sum_{u=1}^{|\mathcal{U}_F|} x_{u,n} P_u g_u + \sigma_0^2} & \end{cases} \quad (2)$$

where  $\mathcal{U}_{MC}$  and  $\mathcal{U}_F$  denote the sets of CMUs and FUs, respectively, and  $|\cdot|$  denotes the cardinality of a finite set. The symbol  $x_{u,n}$  is the SCH allocation parameter, such that  $x_{u,n} = 1$  if the user  $u$  takes SCH  $n$ , otherwise  $x_{u,n} = 0$ .

Now, let  $P_u$  and  $P_{\text{emu}}$  be the transmission powers of the D2D transmitters and EMUs, respectively. Similarly, the received SINR at the MBS for the transmission of EMU  $u'$ , and at the D2D receiver  $u$  on SCH  $n$ , are defined respectively as:

$$\Gamma_{u,n} = \begin{cases} \frac{P_{\text{emu}} h_{u'}}{\sum_{u'=1}^{|\mathcal{U}_{d2d}|} x_{u',n} P_u g_u + \sigma_0^2} & \forall u \in \mathcal{U}_{d2d}, u' \in \mathcal{U}_{ME} \\ \frac{P_u h_u}{\sum_{u'=1}^{|\mathcal{U}_{ME}|} x_{u',n} P_{\text{emu}} g_{u'} + \sigma_0^2} & \end{cases} \quad (3)$$

where  $\mathcal{U}_{ME}$  and  $\mathcal{U}_{d2d}$  denote the sets of EMUs and DUs, respectively. Table 2 provides summary of the notations used in this paper.

TABLE 2. Summary of notations.

Notation	Description
$R$	Coverage radius of the macrocell
$R_c$	Radius of the center zone
$R_f$	Coverage radius of the femtocell
$f_m$	Femtocell $m$
$M$	Number of sectors
$C_i$	$i$ th sector in the center zone
$E_i$	$i$ th sector in the edge zone
$\mathcal{U}_F$	Set of FUs
$\mathcal{U}_{ME}$	Set of EMUs
$\mathcal{U}_{MC}$	Set of CMUs
$\mathcal{U}_{d2d}$	Set of DUs
$\mathcal{U}_C$	Set of CMUs and FUs
$\mathcal{U}_E$	Set of EMUs and DUs
$U_{f_m}$	Number of FUs served by femtocell $m$
$U_{C_i}$	Number of CMUs in sector $C_i$
$N_C$	Number of SCHs assigned to the center zone
$N_E$	Number of SCHs assigned to the edge zone
$\mathcal{B}_C$	SCH set allocated to CMUs and FUs
$\mathcal{B}_{C_i}$	SCH set allocated to the sector $C_i$
$\mathcal{B}_E$	SCH set allocated to EMUs and DUs
$P_u$	Transmission power of FUs and DUs
$\mathbf{p}_f$	Power vector of FUs
$\mathbf{p}_d$	Power vector of DUs
$P_{\max}$	Maximum transmission power of FUs and DUs
$P_{\text{cmu}}$	Transmission power of CMUs
$P_{\text{emu}}$	Transmission power of EMUs
$R_{u,\text{MIN}}$	Minimum rate for user $u$ (bits per channel use)
$T_{u,n}$	Maximum achievable rate of user $u$ on SCH $n$
$x_{u,n}$	SCH allocation parameter for user $u$
$\sigma_0^2$	AWGN power in each SCH
$h_u$	Channel gain for the transmission of user $u$
$g_u$	Interfering channel gain from user $u$ on the common SCH
$w_u^c$	Rate weight of CMU (FU) $u$
$w_u^e$	Rate weight of EMU (DU) $u$
$\mathbf{A}_m$	Admission Matrix for users in $f_m$ and $C_i$
$\mathbf{A}$	Admission matrix for EMUs and DUs
$\mathbf{D}_m$	Decision Matrix for users in $f_m$ and $C_i$
$\mathbf{D}$	Decision Matrix for EMUs and DUs
$\mathbf{X}_m$	SCH assignment matrix for users in $f_m$ and $C_i$
$\mathbf{X}$	SCH assignment matrix for EMUs and DUs
$n_z$	Number of zero rows and columns in $\mathbf{X}_m$ ( $\mathbf{X}$ )
$n_u$	Number of non-zero elements in $\mathbf{X}_m$ ( $\mathbf{X}$ )
$N_m^{\text{ded}}$	Number of SCHs for dedicated use in sector $m$
$N_E^{\text{ded}}$	Number of SCHs for dedicated use in the edge zone
$N_m^{\text{sh}}$	Number of shared SCHs in sector $m$
$N_E^{\text{sh}}$	Number of shared SCHs in the edge zone

### III. PROBLEM FORMULATION

The objective of our problem is to maximize the weighted system sum rate while satisfying a minimum data rate constraint for each individual user and constraints on the maximum transmission powers. In solving this problem, additional constraints related to SCH assignments should be satisfied. An SCH in the set  $\mathcal{B}_C$  can be assigned to at most one FU and one CMU, while an SCH in  $\mathcal{B}_E$  can be assigned to at most one EMU and one DU. The SCH assignment should observe the proposed FFR architecture as well: First, in order to ensure that a CMU located in sector  $C_i$  can only use the SCHs in  $\mathcal{B}_{C_i}$ , the following constraint is required:

$$x_{u,n} = 0, \quad \forall (u, n) | u \in C_i, n \notin \mathcal{B}_{C_i} \quad (4)$$

Similarly, the following constraint is defined to guarantee that an FU served by femtocell  $m$  can only use the SCHs in  $\mathcal{B}_{f_m}$ :

$$x_{u,n} = 0, \quad \forall (u, n) | u \in f_m, n \notin \mathcal{B}_{f_m}, \forall m \quad (5)$$

and the last FFR-related constraint is defined to ensure that the EMUs and DUs do not use the SCHs in  $\mathcal{B}_C$ :

$$x_{u,n} = 0, \quad \forall (u, n) | u \in \{\mathcal{U}_{ME} \cup \mathcal{U}_{d2d}\}, n \notin \mathcal{B}_E \quad (6)$$

According to the Shannon's capacity formula, the maximum achievable data rate (in bits per channel use) from the transmission of user  $u$  on SCH  $n$  is given by:

$$T_{u,n} = \log_2(1 + \Gamma_{u,n}). \quad (7)$$

In summary, the problem of maximizing a weighted sum of the rates of the users in the system subject to the proposed FFR architecture, SCH allocation, maximum transmission power and minimum rate constraints, can be written as follows:

$$\begin{aligned} & \text{maximize} \sum_{n=1}^{N_C} \sum_{u=1}^{|\mathcal{U}_C|} w_u^c x_{u,n} T_{u,n} + \sum_{n=1}^{N_E} \sum_{u=1}^{|\mathcal{U}_E|} w_u^e x_{u,n} T_{u,n} \\ & \text{subject to } C1 : x_{u,n} = 0, \quad \forall (u, n) | u \in C_i, n \notin \mathcal{B}_{C_i} \\ & \quad C2 : x_{u,n} = 0, \quad \forall (u, n) | u \in f_m, n \notin \mathcal{B}_{f_m}, \forall m \\ & \quad C3 : x_{u,n} = 0, \quad \forall (u, n) | u \in \{\mathcal{U}_{ME} \cup \mathcal{U}_{d2d}\}, n \notin \mathcal{B}_E \\ & \quad C4 : \sum_{u=1}^{U_{f_m}} x_{u,n} \leq 1, \quad \forall n \in \mathcal{B}_{f_m}, \forall m \\ & \quad C5 : \sum_{u=1}^{U_{C_i}} x_{u,n} \leq 1, \quad \forall n \in \mathcal{B}_{C_i}, \forall i \\ & \quad C6 : \sum_{u=1}^{|\mathcal{U}_{ME}|} x_{u,n} \leq 1, \quad \forall n \in \mathcal{B}_E \\ & \quad C7 : \sum_{u=1}^{|\mathcal{U}_{d2d}|} x_{u,n} \leq 1, \quad \forall n \in \mathcal{B}_E \\ & \quad C8 : \sum_{n=1}^{N_C} x_{u,n} \leq 1, \quad \forall u \in \{\mathcal{U}_F \cup \mathcal{U}_{MC}\} \\ & \quad C9 : \sum_{n=1}^{N_E} x_{u,n} \leq 1, \quad \forall u \in \{\mathcal{U}_{d2d} \cup \mathcal{U}_{ME}\} \\ & \quad C10 : 0 \leq \sum_{n=1}^{N_C} x_{u,n} P_u \leq P_{\max}, \quad \forall u \in \mathcal{U}_F \\ & \quad C11 : 0 \leq \sum_{n=1}^{N_E} x_{u,n} P_u \leq P_{\max}, \quad \forall u \in \mathcal{U}_{d2d} \\ & \quad C12 : \sum_{n=1}^N x_{u,n} T_{u,n} \geq R_{u,\text{MIN}} \sum_{n=1}^N x_{u,n}, \quad \forall u \\ & \quad C13 : x_{u,n} \in \{0, 1\}, \quad \forall (u, n) \end{aligned} \quad (8)$$

where  $\mathcal{U}_C = \mathcal{U}_{MC} \cup \mathcal{U}_F$  and  $\mathcal{U}_E = \mathcal{U}_{ME} \cup \mathcal{U}_{d2d}$ ,  $w_u^c$  is the weight assigned to the user  $u \in \mathcal{U}_{MC}$ , and  $w_u^e$  is the weight assigned to the user  $u \in \mathcal{U}_{ME}$ . Also,  $\mathbf{X}_C = [x_{u,n}]_{N_C \times |\mathcal{U}_C|}$  and  $\mathbf{X}_E = [x_{u,n}]_{N_E \times |\mathcal{U}_E|}$  denote the SCH allocation matrices in the center zone and edge zone of the macrocell, respectively. The vectors  $\mathbf{p}_f$  and  $\mathbf{p}_d$  are the corresponding transmission power vectors of the FUs and DUs, respectively. Constraints

C1-C3 enforce the proposed FFR scheme. Constraints C4-C5 denote that each SCH of  $\mathcal{B}_C$  can be assigned to at most one FU and one CMU, respectively. Constraints C6-C7 ensure allocating each SCH of  $\mathcal{B}_E$  to at most one cellular EMU and one DU, respectively. Constraints C8-C9 verify that each user accesses at most one SCH. Constraints C10-C11 are the maximum transmission power requirements for the FUs and the DUs, respectively. The minimum rate requirement for the users is imposed by constraint C12. When a user cannot satisfy the minimum rate requirement, the constraint requires it to remain silent (i.e. all  $x_{u,n}$  for that user are zero). Constraint C13 indicates that  $x_{u,n}$  (the SCH allocation parameter) should be a binary value.

#### IV. PROBLEM SOLUTION

Problem (8) is a nonlinear nonconvex mixed integer programming problem, which is hard to solve directly. Our strategy for obtaining good solutions will be to decompose it into three sub-problems, namely, the admission control problem, the power control problem and the SCH allocation/matching problem. In the proposed approach, the admission control, power control, and matching subproblems are solved optimally, and the only suboptimal part of the solution is the heuristic algorithm presented for the SCH allocation.

##### A. ADMISSION CONTROL

Admission control is performed when the number of SCHs is smaller than the number of active users, and thus SCH sharing is needed. An SCH is shared only when the minimum rate requirements of the users can be guaranteed and thus, the interference imposed on the users is below a threshold. In this case, the users sharing the SCH are called an admissible pair. For the admission control portion of the problem (8), admissible pairs in the center zone and the edge zone are determined separately. In the center zone, FUs and CMUs are investigated to determine if they can satisfy the rate requirements while transmitting data on the shared SCHs. If FU  $u$  in femtocell  $m$  shares SCH  $n$  with CMU  $u'$  in sector  $C_i$ , the maximum achievable rates (with each receiver decoding only its own message) are as follows:

$$T_{u,n} = \log_2 \left( 1 + \frac{P_u h_u}{P_{\text{cmu}} g_{u'} + \sigma_0^2} \right), \quad (9)$$

$$T_{u',n} = \log_2 \left( 1 + \frac{P_{\text{cmu}} h_{u'}}{P_u g_u + \sigma_0^2} \right) \quad (10)$$

In this case, considering constraint C12, the following inequalities should be satisfied:

$$T_{u,n} \geq R_{u,\text{MIN}} \quad (11)$$

$$T_{u',n} \geq R_{u',\text{MIN}} \quad (12)$$

The transmission power of FU  $u$  derived from (9) and (11) is:

$$P_u \geq P_u^{lb}, \quad P_u^{lb} = \frac{1}{h_u} \left( 2^{R_{u,\text{MIN}}} - 1 \right) \left( P_{\text{cmu}} g_{u'} + \sigma_0^2 \right) \quad (13)$$

##### Algorithm 1 Admission Control Algorithm for FUs and CMUs

**for** each femtocell  $m$

Define the admission matrix  $\mathbf{A}_m$  of size  $(U_{f_m} \times U_{C_i})$

**for** each FU  $u \in f_m$

**for** each CMU  $u' \in C_i$

**if** inequality (17) is satisfied then,

Set  $\mathbf{A}_m(u, u') = 1$

**end if**

**end for**

**end for**

**end for**

Similarly, the transmission power of FU  $u$  derived from (10) and (12) is:

$$P_u \leq \frac{1}{g_u} \left( \frac{P_{\text{cmu}} h_{u'}}{2^{R_{u',\text{MIN}}} - 1} - \sigma_0^2 \right), \quad (14)$$

and from constraint C10,

$$P_u \leq P_{\text{max}}. \quad (15)$$

Therefore, from (14) and (15):

$$P_u \leq P_u^{ub}, \quad \text{where:} \\ P_u^{ub} = \min \left\{ P_{\text{max}}, \frac{1}{g_u} \left( \frac{P_{\text{cmu}} h_{u'}}{2^{R_{u',\text{MIN}}} - 1} - \sigma_0^2 \right) \right\} \quad (16)$$

Furthermore, from (13) and (16), we have:

$$P_u^{lb} \leq P_u^{ub} \quad (17)$$

Now, the inequality (17) can be used for determining admissible FU-CMU pairs as described in Algorithm I. The admission control in Algorithm I is performed for each femtocell separately, where the inequality (17) is checked for all the FU-CMU pairs in that femtocell and its related central sector. If (17) holds for a given FU-CMU pair, that pair is determined to be an admissible pair. The output of the algorithm is a binary admission matrix  $\mathbf{A}_m$  whose entries are set to 1 when (17) is satisfied.

For admission control in the edge zone, the same procedure is carried out to find admissible D2D-EMU pairs. Considering the minimum rate requirements of the users and the maximum transmission power of the DUs, the following condition can be derived:

$$P_u^{lb} \leq P_u^{ub} \quad \forall u \in \mathcal{U}_{d2d}, \quad \forall u' \in \mathcal{U}_{ME}, \quad (18)$$

where

$$P_u^{lb} = \frac{1}{h_u} \left( 2^{R_{u,\text{MIN}}} - 1 \right) \left( P_{\text{emu}} g_{u'} + \sigma_0^2 \right), \\ P_u^{ub} = \min \left\{ P_{\text{max}}, \frac{1}{g_u} \left( \frac{P_{\text{emu}} h_{u'}}{2^{R_{u',\text{MIN}}} - 1} - \sigma_0^2 \right) \right\} \quad (19)$$

The proposed scheme for achieving admissible D2D-EMU pairs in the edge zone is described in Algorithm II. This algorithm determines the admission matrix  $\mathbf{A}$  for the EMUs.

**Algorithm 2** Admission Control Algorithm for EMUs and DUs

```

Define the admission matrix  $\mathbf{A}$  of size  $(|\mathcal{U}_{d2d}| \times |\mathcal{U}_{ME}|)$ 
for each DU  $u$ 
  for each EMU  $u'$ 
    if inequality (18) is satisfied then,
      Set  $\mathbf{A}(u, u') = 1$ 
    end if
  end for
end for
    
```

**B. POWER CONTROL**

In this section, the potential transmission powers of FUs and DUs are calculated (The actual powers to be employed will be selected by the SCH allocation and matching algorithm in Section. IV.C). When FU  $u$  and CMU  $u'$  use the same SCH, the weighted achievable rate maximization problem for them can be written as follows:

$$\begin{aligned}
 & \underset{P_u}{\text{maximize}} \quad w_u^c \log_2 \left( 1 + \frac{P_u h_u}{P_{\text{cmu}} g_{u'} + \sigma_0^2} \right) \\
 & \quad + w_{u'}^c \log_2 \left( 1 + \frac{P_{\text{cmu}} h_{u'}}{P_u g_u + \sigma_0^2} \right) \\
 & \text{subject to } C1 : T_{u,n} \geq R_{u,\text{MIN}} \\
 & \quad C2 : T_{u',n} \geq R_{u',\text{MIN}} \\
 & \quad C3 : P_u \leq P_{\text{max}} \tag{20}
 \end{aligned}$$

Using an analysis similar to the analysis that led to (17), we can simplify the constraints. Consequently, if we let  $f(P_u)$  denote the function in (26) in Appendix, which is equivalent to the objective in (20), the optimal solution to (20) is either the point  $P_u^*$  at which  $\partial f / \partial P_u = 0$ , if that point is feasible, or one of the end points determined by the problem constraints. However, according to the proof provided in Appendix,  $P_u^*$  (when it is feasible) is a minimizer point. Therefore, the optimal solution to (20) occurs at one of the end points determined by the problem constraints. The optimal transmission power for each FU considering its admissible partners among the CMUs can be simplified to:

$$P_u^{\text{opt}} = \arg \max_{P_u \in \mathcal{P}} f(P_u) \text{ where } \mathcal{P} = \{P_u^{\text{lb}}, P_u^{\text{ub}}\} \tag{21}$$

The output of the power control algorithm for each femtocell is a matrix of size  $(U_{f_m} \times U_{C_i})$ , each entry of which represents the optimal transmission power of the FUs when they share an SCH with each CMU.

The same procedure is carried out for achieving potential optimum transmission powers of the DUs. The output of the power control algorithm for the DUs is a matrix of size  $(|\mathcal{U}_{d2d}| \times |\mathcal{U}_{ME}|)$ , each entry of which represents the optimal transmission power of the D2D transmitters when they share an SCH with each EMU.

It is worth mentioning that, when an FU (or a DU) takes a dedicated SCH, its transmission power is set to the maximum transmission power.

**C. SCH ALLOCATION AND MATCHING**

In this section, SCH allocation is performed for all the users so that the users selected for transmitting data on shared SCHs are matched, and the users transmitting on dedicated SCHs and those remaining silent are determined. To this end, a heuristic scheme is proposed. In the proposed scheme, the admission matrices are acquired first through the algorithms proposed in Section IV.A. In the next step, after calculating the potential optimal transmission power for the FUs and D2D transmitters using the algorithm in Section IV.B, the optimal combination for the matching of the FU-CMU or DU-EMU pairs is determined (so that the maximum weighted sum rate is acquired) by using the Kuhn-Munkres algorithm, which is a matching algorithm that searches among the possible combinations to find the optimum assignments [29]. The inputs of the Kuhn-Munkres algorithm are the decision matrices  $\mathbf{D}_m$  and  $\mathbf{D}$  for the sector  $m$  and the edge zone, respectively. The decision matrix is achieved by calculating the weighted sum rate for FU-CMU (or DU-EMU) pairs related to the non-zero entries in the admission matrix. Then, the final transmission power vectors  $\mathbf{p}_f$  and  $\mathbf{p}_d$  are chosen from the potential power allocation matrices according to the results of the matching algorithm. The output of the matching algorithm is a zero-one assignment matrix (denoted by  $\mathbf{X}_m$  for the central sector  $m$ , and  $\mathbf{X}$  for the edge zone), which has a maximum of one non-zero value element in each row and each column related to the users sharing an SCH for transmission. Therefore, when  $\mathbf{X}_m(u, u') = 1$  (or  $\mathbf{X}(u, u') = 1$ ), the corresponding element in the potential power matrix is considered as the transmission power for the user  $u$ . Also, as not all the users can take the SCHs in a reuse way necessarily (zero rows or zero columns may exist in the output matrix), it is necessary to determine the users that should occupy dedicated SCHs. Assuming  $n_u$  represents the number of non-zero elements in the assignment matrix, the number of remaining SCHs for dedicated transmission in the center and edge zones of the macrocell is respectively calculated as follows:

$$N_m^{\text{ded}} = |\mathcal{B}_{C_m}| - n_u \tag{22}$$

$$N_E^{\text{ded}} = N_E - n_u \tag{23}$$

As the aim is to maximize the weighted sum rate of the system in a greedy way, users related to the zero rows and zero columns are identified and sorted based on the weighted rates they would obtain by transmitting on dedicated SCHs, in descending order. Then, the minimum rate constraints are checked and the users which cannot satisfy the minimum rate even on the dedicated SCH are removed from the list and stay silent. The remaining SCHs in each sector of  $\mathcal{B}_C$  are assigned, in a dedicated fashion, to the first  $N_m^{\text{ded}}$  users in the list regardless of being an FU or a CMU and, the remaining SCHs in  $\mathcal{B}_E$  are assigned, in a dedicated fashion, to the first  $N_E^{\text{ded}}$  users in the list regardless of their transmission mode (D2D or cellular) in the edge zone.

In the case that the number of zero rows and zero columns in the assignment matrix, denoted by  $n_z$ , is lower than the

number of dedicated SCHs,  $N_m^{\text{sh}}$  (or  $N_E^{\text{sh}}$ ) pairs of FU-CMU (or DU-EMU) pairs with the maximum entries in the decision matrix  $\mathbf{D}_m$  (or  $\mathbf{D}$ ) are chosen for transmission in the reuse mode, where:

$$N_m^{\text{sh}} = (U_{f_m} + U_{C_i}) - |\mathcal{B}_{C_m}| \quad (24)$$

$$N_E^{\text{sh}} = |\mathcal{U}_{d2d}| + |\mathcal{U}_{ME}| - N_E \quad (25)$$

Afterwards, the remaining SCHs are assigned, in a dedicated fashion, to the remaining users of the related zone, if they can satisfy the minimum rate requirements. This ensures that no SCH stays unused, and the maximum sum rate is achieved. Algorithms III and IV describe the overall proposed scheme to generate good solutions to the problem (8) for  $\mathcal{B}_C$  and  $\mathcal{B}_E$ , respectively.

It is worth noting that if the number of users is smaller than the available SCHs, the proposed algorithms are not performed. Instead, a dedicated SCH is assigned to the users (randomly) and their transmission power is set to the maximum permissible value.

## V. PERFORMANCE EVALUATION

In this section, the performance of our approach is evaluated through the complexity analysis and numerical results and is compared to the Branch & Bound (B&B) approach and a random assignment approach. B&B is an effective scheme to solve the NP-hard problems like problem (8). Although it finds an optimal solution to the problem, it has a very high computational complexity [30]. In the random scheme, the users that would transmit on shared and dedicated SCHs in each zone and sector of the macrocell are determined in a random fashion. The users that are selected to work in the reuse mode are also matched randomly, while the problem constraints related to the SCH allocation and proposed FFR architecture are observed. Then, the transmission power of FUs and DUs is obtained using the power control algorithm proposed in Section IV.B. Finally, the minimum rate requirement of the users is investigated. When two matched users cannot satisfy the minimum rates in the reuse mode, one with the higher achievable rate uses the dedicated SCH, and the other remains silent. Also, if the user rate constraint on the dedicated SCH is not satisfied, the SCH remains unused.

### A. COMPLEXITY ANALYSIS

Let us assume that  $|\mathcal{U}_{ME}| = N_1$  and  $|\mathcal{U}_{d2d}| = N_2$ , and  $N_1 \geq N_2$ . In Algorithm IV, the calculation of the admission matrix  $\mathbf{A}$ , optimum transmission power from equation (21) and the elements of matrix  $\mathbf{D}$  for DUs and EMUs entails  $N_1 N_2$  operations. The Kuhn-Munkres Algorithm has a time complexity of  $O(N_1^3)$ . Finding  $U^{\text{ded}}$  users related to the zero rows and zero columns in  $\mathbf{X}$  with highest values of weighted rates requires a worst-case complexity of  $N_1 \log_2 N_1$ . Therefore, checking the minimum rate requirements and assigning SCHs to those  $U^{\text{ded}}$  selected users needs  $N_1 + U^{\text{ded}} + N_1 \log_2 N_1$  operations. The total complexity of Algorithm IV is thus  $O(N_1 N_2 + N_1^3 + N_1 + U^{\text{ded}} + N_1 \log_2 N_1) \approx O(N_1^3)$ .

### Algorithm 3 Overall Proposed Scheme for Solving Problem (8) Part I

---

```

for  $m = 1 : M$ 
  for each FU  $u \in f_m$ 
    for each CMU  $u' \in C_i$ 
      Find  $\mathbf{A}_m(u, u')$  from Algorithm I.
      if  $\mathbf{A}_m(u, u') = 1$ ,
        Find  $P_u^{\text{opt}}$  from (21)
        Calculate Decision Matrix  $\mathbf{D}_m$  where:
           $\mathbf{D}_m(u, u') = w_u^c \log_2(1 + \frac{P_u^{\text{opt}} h_u}{P_{\text{cmu}} g_{u'} + \sigma_0^2})$ 
             $+ w_{u'}^c \log_2(1 + \frac{P_{\text{cmu}} h_{u'}}{P_u^{\text{opt}} g_u + \sigma_0^2})$ 
        else,
          Set  $\mathbf{D}_m(u, u') = 0$ .
        end if
      end for
    end for
  Set  $\mathbf{D}_m$  as the input of the Kuhn-Munkres algorithm
  Obtain the output matrix  $\mathbf{X}_m$ ,
  Find  $n_z$ , the number of zero rows and zero columns in  $\mathbf{X}_m$ ,
  Calculate  $N_m^{\text{ded}}$  from (22)
  if  $n_z \geq N_m^{\text{ded}}$ 
    Set  $N_m^{\text{sh}} = n_u$ ,
    Sort users related to the zero rows and zero columns in
       $\mathbf{X}_m$  based on their achievable weighted rates  $w_u^c T_u$  and
       $w_{u'}^c T_{u'}$  in the descending order where:
       $T_u = \log_2(1 + \frac{P_{\text{max}} h_u}{\sigma_0^2})$ ,
       $T_{u'} = \log_2(1 + \frac{P_{\text{cmu}} h_{u'}}{\sigma_0^2})$ ,
    Remove users not satisfying the rate requirement from the
    list,
    Assign dedicated SCHs to the first  $N_m^{\text{ded}}$  users in the list,
    else
      Calculate  $N_m^{\text{sh}}$  from (24),
      Choose  $N_m^{\text{sh}}$  pairs with the maximum entries in  $\mathbf{D}_m$  for the
      reuse mode,
      Assign dedicated SCHs to the remaining users, if they
      satisfy the
        minimum rate requirements.
    end if
  end for

```

---

With a similar analysis, the total complexity of Algorithm III is  $O(M(MU_{f_m} U_{C_i} + U_{C_i}^3 + U_{C_i} + U^{\text{ded}} + U_{C_i} \log_2 U_{C_i})) \approx O(MU_{C_i}^3)$ .

Therefore, compared with the B&B search algorithm, for which the worst-case time complexity is exponential, the proposed algorithms have much lower complexity.

### B. SIMULATION RESULTS

Fig. 2 shows a typical configuration of the simulated network. If we denote the radius of the macrocell by  $R$ , in order to maximize the average network throughput, the center-zone radius  $R_c$  is set to  $0.65R$  [31]. Other than the base station,



**Algorithm 4** Overall Proposed Scheme for Solving Problem (8) Part2

```

for each DU  $u \in \mathcal{U}_{d2d}$ 
  for each EMU  $u' \in \mathcal{U}_{ME}$ 
    Find  $\mathbf{A}(u, u')$  from Algorithm II.
    if  $\mathbf{A}(u, u') = 1$ ,
      Find  $P_u^{\text{opt}}$  from (21)
      Calculate Decision Matrix  $\mathbf{D}$  where:
      
$$D(u, u') = w_u^e \log_2 \left( 1 + \frac{P_u^{\text{opt}} h_u}{P_{\text{emu}} g_{u'} + \sigma_0^2} \right) + w_{u'}^e \log_2 \left( 1 + \frac{P_{\text{emu}} h_{u'}}{P_u^{\text{opt}} g_u + \sigma_0^2} \right)$$

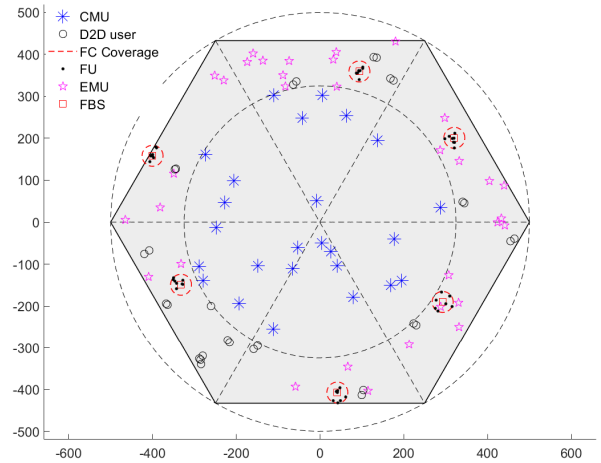
      else,
        Set  $\mathbf{D}(u, u') = 0$ .
      end if
    end for
  end for
Set  $\mathbf{D}$  as the input of the Kuhn-Munkres algorithm,
Obtain the output matrix  $\mathbf{X}$ ,
Find  $n_z$ , the number of zero rows and zero columns in  $\mathbf{X}$ ,
Calculate  $N_E^{\text{ded}}$  from (23)
if  $n_z \geq N_E^{\text{ded}}$ 
  Set  $N_E^{\text{sh}} = n_z$ ,
  Sort users related to the zero rows and zero columns in  $\mathbf{X}$  based on their achievable weighted rates  $w_u^e T_u$  and  $w_{u'}^e T_{u'}$  in the descending order where:
  
$$T_u = \log_2 \left( 1 + \frac{P_{\text{max}} h_u}{\sigma_0^2} \right),$$

  
$$T_{u'} = \log_2 \left( 1 + \frac{P_{\text{emu}} h_{u'}}{\sigma_0^2} \right),$$

  Remove users not satisfying the rate requirement from the list,
  Assign dedicated SCHs to the first  $N_E^{\text{ded}}$  users in the list,
else
  Calculate  $N_E^{\text{sh}}$  from (25),
  Choose  $N_E^{\text{sh}}$  pairs with the maximum entries in  $\mathbf{D}$  for the reuse mode,
  Assign dedicated SCHs to the remaining users, if they satisfy the minimum rate requirements.
end if

```

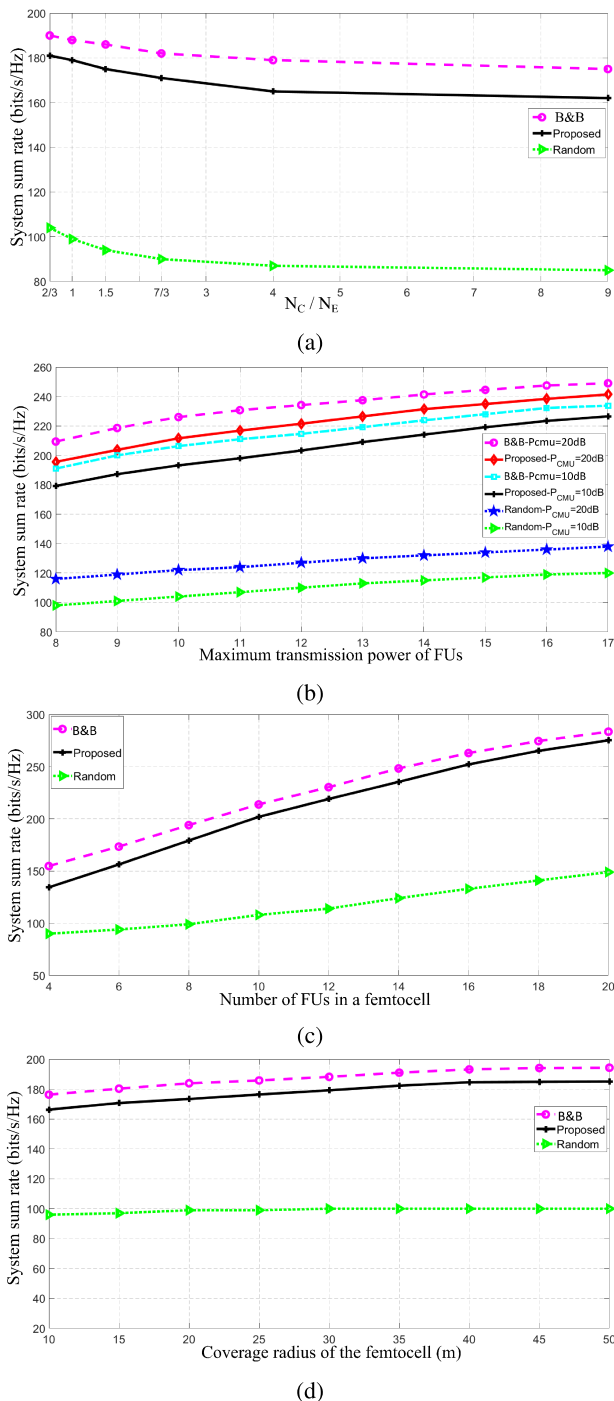
all components in the network are distributed randomly, with a random number of CMUs in the range of  $[1, \frac{N_C}{M}]$  being distributed uniformly in each sector of the center zone. The EMU and D2D transmitters are also distributed uniformly in the edge zone of the macrocell and each D2D receiver is distributed uniformly within the radius  $R_{d2d}$  of the relevant D2D transmitter. An FBS is scattered uniformly in each sector of the edge zone, and  $U_{f_m}$  FUs are located within the coverage area of  $m^{\text{th}}$  femtocell with the uniform distribution. The available uplink bandwidth is 12 MHz, which is divided into 120 SCHs with equal bandwidths of 100kHz. The minimum rate requirement for all the users is uniformly distributed in (0,300) kbps, which corresponds to (0,3) bits per channel use.



**FIGURE 2.** A typical configuration of the simulated network.

For the calculation of channel gains on each link, path loss, shadowing, and fast fading are considered. The shadowing has a log-normal distribution with standard deviation of 4dB and 8dB for inside the femtocell and outside the femtocell, respectively, and the fast fading is modeled by independently and identically distributed Rayleigh random variables with unit variance. The path loss is  $PL = 127 + 30 \log_{10}(d)$  if the link (both the transmitter and receiver) is in a femtocell, otherwise, it is defined as  $PL = 128.1 + 37.6 \log_{10}(d)$ , where  $d$  is the distance between the transmitter and the receiver in km and PL is in dB [32].

Fig. 3a shows the equally weighted system sum rate for the proposed, B&B, and random schemes when  $N_C/N_E$  changes from 2/3 to 9. In particular,  $N_C$  increases from 48 to 108 while  $N_E$  is reduced from 72 to 12. In this scenario, an equally fixed power allocation (8dBm) is considered for DUs, while the proposed power control is applied for FUs. All other simulation parameters are set to the default values given in Table 3. It is shown that the performance of the proposed scheme is close to that of the B&B approach and very much better than that of the random approach. This is a predictable result as in the proposed approach the admission control, power control and matching sub-problems have all been solved by the optimum methods and the only sub-optimal part of the solution is the heuristic algorithm presented for the SCH allocation. Also, the run time of the proposed algorithm is much less than that of the B&B algorithm (typically a run time of the B&B is 500 times longer than that of the proposed scheme). From Fig. 3a, it can be seen that as the ratio  $N_C/N_E$  increases, the sum rate decreases; because, the number of CMUs and EMUs are random values uniformly distributed within  $[1, N_C]$ , and  $[1, N_E]$ , respectively. Therefore, when  $N_C$  increases, the number CMUs increases, and the sum rate improves because of the resulted user diversity. On the other hand,  $N_E$  is reduced, which leads to a reduction in the number of EMUs. Therefore, the user diversity is reduced and the sum rate decreases. As seen, the resultant of increasing  $N_C$  and decreasing  $N_E$  is the reduction in the system sum rate. Indeed, the reduction of the sum rate that results from decreasing



**FIGURE 3.** Performance of the proposed scheme compared with the random and optimal schemes.

$N_E$  dominates the increase in the sum rate, that results from increasing  $N_C$ . This is because in the center zone, there are two groups of constraints (the maximum power constraint of FUs and minimum rate constraint of FUs and CMUs), which narrow the feasible region of the problem considerably. Therefore, the sum rate improvement is not significant. In the edge zone, however, the transmission power of DUs is constant, and the minimum rate constraint on the users is the only factor that narrows the feasible region of the problem.

**TABLE 3.** Simulation parameters.

Para.	Values	Para.	Values
$M$	6	$\sigma_0^2$	-174dBm/Hz
$\bar{R}$	500m	$R_{u,MIN}$	$\sim U(0, 300)$ kbps
$R_c$	325m	$N_C$	60
$R_f$	25m	$N_E$	60
$R_{d2d}$	10m	$U_{f_m}$	8
$B$	12MHz	$U_{C_i}$	$\sim U(1, \frac{N_C}{M})$
$ U_{ME} $	$\sim U(1, N_E)$	$ U_{d2d} $	10
$P_{emu}$	12dBm	$P_{cmu}$	10dBm
$P_{max}$	8dBm	runs	3000

Therefore, the reduction in user diversity considerably affects the sum rate of the edge zone and thus the resultant performance decreases. When the value of  $N_C/N_E$  is greater than 4, the sum rate does not change significantly and the effect of the reduction in  $N_E$  is neutralized by the increase in  $N_C$  from this point.

The curve related to the random scheme has a similar decreasing trend as the proposed and optimal schemes, although the sum rate is much lower. The reason is that the matching and SCH allocation procedures are performed in a random fashion, and the minimum constraints on the users' rates are checked at the end of the algorithm.

Fig. 3b compares the system sum rate of the proposed scheme with those of the B&B and random methods with respect to the maximum transmission power of the FUs when the transmission power of the CMUs is set to two different values, 10dBm and 20dBm. It can be seen that the performance of the proposed scheme is close to that of the optimal method. Furthermore, the increasing trend of the sum rate slows for higher values of  $P_{max}$ . This is because when  $P_{max}$  is low, the maximum power constraint becomes the major factor that restricts the feasible region of the problem, whereas when  $P_{max}$  increases, the cross-tier interference becomes more significant, and thus the minimum rate constraint of the users becomes the major factor for determining the feasible solutions and this constrains the increase in the sum rate. As can be seen, increasing the transmission power of the CMUs and FUs has a positive effect on the system sum rate in all three schemes. However, in the random scheme, the increasing trend with respect to  $P_{max}$  is slow and the sum rate remains constant for higher values of  $P_{max}$ . This is because there is no admission control in the random scheme, and the SCH allocation is performed without consideration of the minimum rate constraints.

The system sum rate versus the number of FUs in each femtocell is illustrated in Fig. 3c, where it can be seen that the performance of the proposed scheme is close to that of the B&B scheme, especially for higher values of the number of FUs. Furthermore, the sum rate distinctly increases with the increase in the number of FUs. This is because when the number of FUs is low, there is a greater possibility that there exist enough empty SCHs for all the users to take dedicatedly and there is no need to reuse SCHs. Hence, no reuse gain is achieved. Furthermore, with the increase in the number of FUs, more SCHs are reused by FUs and CMUs

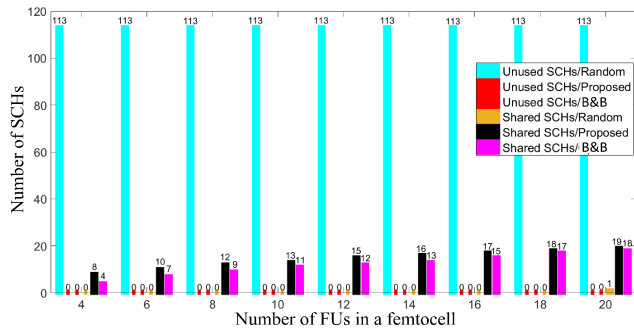


FIGURE 4. Assignment of SCHs in the macrocell versus the number of FUs.

due to the inherent multiuser diversity and thus, the sum rate increases.

It can also be seen that the increasing trend of the sum rate in the random scheme becomes faster when  $U_{fm}$  is higher than 10. The reason is that the number of SCHs assigned to each sector of the center zone (and each femtocell) is 10, and thus when the number of FUs becomes higher than 10, the benefit that the random scheme derives from the multiuser diversity becomes more considerable.

Fig. 3d depicts the system sum rate versus the coverage radius of the femtocell. The performance of the proposed method is, once again, close to that of the optimal B&B method. Also, the sum rate increases slowly with the increase of the radius; because, when the coverage radius of the femtocell is extended, the channel gains of the links change, and the condition for satisfying the admission control inequality becomes more appropriate, and thus the system benefits from the reuse gain. Also, it is observed that the coverage radius of the femtocell does not have any significant influence on the system performance in the random scheme. Indeed, in the random scheme, the coverage radius of the femtocell does not affect the transmission mode selection or the matching procedure; because, the transmission mode (reuse or dedicated) of the users is selected randomly, and the matching procedure for the reuse mode users is performed in a random fashion, as well. Consequently, the reuse gain does not change. The value of the femtocell radius only affects the channel gains and the allocated transmission power to the users (members of  $\mathcal{P}$ ); therefore, as seen in Fig. 3d, the resultant effect on the achievable rate of the users is insignificant.

Fig. 4 illustrates the assignment of SCHs for the three considered schemes when the number of FUs changes from 4 to 20. In the random approach, the number of unused SCHs is always very high while the number of shared SCHs is almost zero. This is due to the fact that the SCHs that are to be shared, and those to be dedicated to one user, are determined based on the random strategy. Then, the proposed power control is performed, and the rate constraints of the users are checked at the end of the process. Therefore, if the minimum rate constraints of the users on the shared SCH are not met, the SCH is occupied by the user with the higher achievable rate, and if the user rate constraint on the dedicated SCH is not satisfied, the SCH remains unused. From Fig. 4, the number of unused SCHs in the proposed scheme and

the optimal scheme is always zero. The reason is that the proposed heuristic approach assigns SCHs of each sector in a way that none of the SCHs remain unused, unless the number of assigned SCHs for a region is higher than the total number of the active users in that region. In order to have a better comparison, empty SCHs are not considered in the data illustrated in Fig. 4 for the situations in which the number of assigned SCHs for a region is higher than the number of total active users. The difference between the number of shared SCHs in the proposed and optimal schemes results from the sub-optimal heuristic algorithm for the SCH assignment. This difference is not significant, especially for the higher values of  $U_{fm}$ , where the performance of the proposed scheme is very close to that of the optimal scheme (as seen also in Fig. 3c).

## VI. CONCLUSION

In this paper, the problem of weighted sum rate maximization for the uplink of a three-tier HetNet including a macrocell with cellular users, D2D devices and femtocells with femto users is tackled. The minimum rate requirements of all users and power constraints of the FUs and DUs are taken into account in the maximization problem. In the proposed system model, all the devices can access the spectrum in dedicated or reuse modes. In order to reduce the cross-tier interference among the macrocell and femtocell users and prevent the co-tier interference among the femtocells, a new FFR method is proposed as well. To solve the mixed integer nonlinear nonconvex problem, an approach based on problem decomposition method is presented. In the proposed scheme, admission control is performed optimally by two algorithms in which potential user pairs are identified for sharing an SCH in two simultaneous transmissions according to the power and rate requirements of the users. Afterwards, the power control optimization problem is optimally solved and closed-form solutions for the transmission power of FUs are obtained. For the matching problem, the Kuhn-Munkres algorithm is used. Finally, a heuristic algorithm is proposed to determine which users should transmit on dedicated or shared SCHs, so that the system sum rate is elevated. Numerical results verify the effectiveness of the proposed scheme, showing that it performs much better than the random scheme, and achieves 93% of the optimum B&B performance in the worst case. In addition, the proposed solution has a much lower computational cost than the B&B algorithm. This paper also opens multiple future directions. One future direction is to consider a dynamic power allocation for the CMUs and EMUs, and find the optimal transmission power for all the users. Another potential direction for the future work is to find solutions for the problem when multiple SCHs are shared among the users. Finally, beamforming techniques can be utilized to achieve enhanced interference mitigation and spatial reuse capability.

## APPENDIX

*Theorem: The extreme point of the objective in (20) is a minimizer point, if it is feasible.*

*Proof:* As logarithm is a monotonically increasing function, the objective in (20) is equivalent to:

$$f(P_u) = \left(1 + \frac{P_u h_u}{P_{\text{cmu}} g_{u'} + \sigma_0^2}\right) \left(1 + \frac{P_{\text{cmu}} h_{u'}}{P_u g_u + \sigma_0^2}\right) \quad (26)$$

We search for feasible extreme points by differentiating  $f(P_u)$  with respect to  $P_u$ :

$$\frac{\partial f}{\partial P_u} = \frac{A(P_u)^2 + 2BP_u + C}{D} \quad (27)$$

where

$$\begin{aligned} A &= (g_u)^2 h_u, \\ B &= g_u h_u \sigma_0^2, \\ C &= -\sigma_0^2 P_{\text{cmu}} g_u h_{u'} - P_{\text{cmu}}^2 g_u g_{u'} h_{u'} \\ &\quad + \sigma_0^4 h_u + \sigma_0^2 h_u P_{\text{cmu}} h_{u'} \\ D &= (P_u g_u + \sigma_0^2)^2 (P_{\text{cmu}} g_{u'} + \sigma_0^2) \end{aligned} \quad (28)$$

Since  $D$  is always positive, the stationary point in which  $\partial f / \partial P_u = 0$  can be found by solving  $A(P_u)^2 + 2BP_u + C = 0$ , yielding:

$$P_u = \frac{(-B \pm \sqrt{B^2 - AC})}{A} \quad (29)$$

As  $A, B > 0$ ,  $C$  cannot be greater than zero; because, if  $C > 0$ , according to (29),  $P_u$  will be a negative or non-real value. But, we are only interested in positive real-valued  $P_u \in [0, P_{\text{max}}]$ , denoted by  $P_u^*$ . Thus, we investigate the extreme points of the objective function regarding the condition  $C \leq 0$ . To find out whether  $P_u^*$  is a minimizer or maximizer of the function  $f(P_u)$ , the second derivative is calculated:

$$\frac{\partial^2 f}{\partial P_u^2} = \frac{E \cdot F}{G} \quad (30)$$

where

$$\begin{aligned} E &= g_u \sigma_0^2 + P_{\text{cmu}} g_u g_{u'} - \sigma_0^2 h_u \\ F &= 2g_u h_{u'} P_{\text{cmu}}, \quad F > 0 \\ G &= (P_u g_u + \sigma_0^2)^3 (P_{\text{cmu}} g_{u'} + \sigma_0^2), \quad G > 0 \end{aligned} \quad (31)$$

As  $F, G > 0$ ,  $\partial^2 f / \partial P_u^2$  is non-negative if  $E \geq 0$ , and the following inequality should hold:

$$g_u (P_{\text{cmu}} g_{u'} + \sigma_0^2) \geq \sigma_0^2 h_u \quad (32)$$

Now, from (26), we can see that  $C \leq 0$  implies that:

$$g_u (P_{\text{cmu}} g_{u'} + \sigma_0^2) \geq (\sigma_0^2 h_u) \left( \frac{\sigma_0^2}{P_{\text{cmu}} h_{u'}} + 1 \right) \quad (33)$$

Since  $\frac{\sigma_0^2}{P_{\text{cmu}} h_{u'}}$  is a positive value, and thus  $\frac{\sigma_0^2}{P_{\text{cmu}} h_{u'}} + 1$  is greater than 1, we have:

$$(\sigma_0^2 h_u) \left( \frac{\sigma_0^2}{P_{\text{cmu}} h_{u'}} + 1 \right) \geq \sigma_0^2 h_u \quad (34)$$

Therefore, we can write the inequality (33) as follows:

$$g_u (P_{\text{cmu}} g_{u'} + \sigma_0^2) \geq \sigma_0^2 h_u, \quad (35)$$

which demonstrates that  $\frac{\partial^2 f}{\partial P_u^2} \geq 0$ . Consequently,  $f(P_u)$  is a convex function with respect to  $0 \leq P_u \leq P_{\text{max}}$ , and  $P_u^*$  is a minimizer point.

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