Wireless Resource Virtualization With Device-to-Device Communication Underlaying LTE Network

Abdallah Moubayed, Abdallah Shami, and Hanan Lutfiyya

***Abstract*—Wireless resource virtualization is a potential solution for meeting the increasing demand for mobile data services. Virtualization allows for more efficient utilization of the spectrum, reduces capital expenditures and operating expenditures, and can support higher peak rates. Device-to-device (D2D) communication as an underlay to cellular networks is also a potential solution to satisfy the data demand. Due to the proximity of devices and thus the higher signal-to-interference and noise ratio, higher data rates can be achieved using D2D communication. This is beneficial in cases of multimedia sharing where data can be broadcast to several nearby users. However, the interference that D2D pairs introduce to cellular users should be below a target threshold so as not to reduce their performance. In this paper, the problem of wireless resource virtualization with D2D communication underlaying the LTE network is formulated. Since the problem is an integer non-linear programming problem, it is divided into two smaller linear integer programs that are solved to optimality. Two lower complexity heuristic algorithms, each solving one of the subproblems are introduced. Results show that the heuristic achieves close to optimal results while having a much lower computational complexity.**

***Index Terms*—Wireless resource virtualization, device-to-device communication, LTE, spectrum management techniques.**

I. Introduction

THE ADVANCEMENT and penetration of cellular technology has led to the increase of wireless spectrum licensing [1]. Consumers for new services such as satellite digital audio broadcasting and wireless Internet access are quickly increasing by hundreds of millions [2]. This has caused a dramatic growth in the spectrum access demand. However, it is becoming more difficult to provide spectrum for new services or expanding existing ones with most of the spectrum already being assigned [1]. Yet, studies performed in the USA show that the problem is often a spectrum access problem rather than the lack of available spectrum, meaning there is unexploited capacity in the spectrum [3]. Also, with the profit growth rate being less than the mobile data services' demand rate [4], service providers (SPs) are searching for innovative solutions to satisfy the growing demand while increasing their average revenue per user concurrently [2].

Wireless resource virtualization (WRV) has been suggested as a potential solution [5]–[8]. WRV can be defined as the slicing of the wireless resources and the sharing of the physical infrastructure among co-existing networks in a dynamic manner in order to efficiently utilize the available resources [7]. It can also be defined as the abstraction and sharing of wireless hardware equipment by multiple virtual owners, also known as tenants [8]. WRV offers several benefits to the different SPs. First, it helps improve the utilization of resources due to SPs sharing them, thus reducing the number of idle resources. Second, WRV can reduce the capital expenditures (CAPEX) by almost 80% and operating expenditures (OPEX) by almost 27% [9]. Also, WRV can support higher peak rates due to carrier resource aggregation and radio resource sharing between different SPs. Finally, multi-SP multiplexing gain is introduced as a result of the increased number of users in the cells. For example, the aggregated cell capacity increasing by ln M in a Rayleigh fading channel where M is the number of users in the cell [10]. Adaptive resource allocation techniques can further augment the benefits of WRV, especially in orthogonal frequency division multiple access-based (OFDMA) systems such as in LTE downlink [11]–[13].

Another proposed solution to meet the increasing demand is employing Device-to-Device (D2D) communication as an underlay to cellular networks. D2D communication is defined to be the direct communication between users' equipment (UEs) that are close to each other and have a higher signal-to-interference plus noise ration (SINR) without having to send the data through the base station [14]–[17]. These UEs can achieve higher rates than that offered by sending data through the base station because of the better SINR they have. Also, D2D communication can decrease the load at the base station since some content is downloaded directly without going through the base station. This would be beneficial in several applications. For example, D2D communication can be used for real-time gaming or content distribution among large crowds [16]. It can also be used for multimedia sharing where a large group of devices can share multimedia files without overburdening the base station with requests which leads to cellular offloading [18]. However, when D2D communication is employed as an underlay to cellular networks, the interference to the cellular users should be restricted to maintain the quality-of-service (QoS) requirement of these users [19], [20].

Both possible solutions are combined in this paper. The problem of wireless resource virtualization with device-to-device communication underlaying cellular network is formulated. The problem is solved using two different schedulers.

This paper is organized as follows. Section II discusses some of the related work done in the literature. Section III presents the system model as well as the channel model. The optimization problem is presented in Section IV. The heuristic algorithms are described in Section V. Section VI presents the simulation parameters and results. Finally, Section VII concludes the paper.

II. Related Work

Wireless resource virtualization has garnered increasing attention in recent times. Several literature works investigated this idea from different aspects. A survey of the works done on wireless virtualization as well as the models adopted and challenges encountered was presented in [21]. Two WRV schemes are described, namely infrastructure sharing and full network sharing. In the first scheme, only the physical infrastructure such as the eNodeBs and antennas are shared. In the second scheme, both the spectrum and the physical infrastructure are shared among the different SPs. Two business models were proposed. The first model is a two-level model that contains

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two different entities: mobile network operators (MNOs) that own and operate the infrastructure as well as the radio resources and execute the virtualization scheme, and the service providers (SPs) that provide end-to-end services to mobile users by leasing and programming the virtual resources. The second model is a three-level model consisting of the infrastructure providers (InPrs), the mobile virtual network operators (MVNOs), and the SPs. The InPr own the physical infrastructure and the radio resources. The MVNOs create virtual resources and allocate them to SPs after leasing the resources from the InPrs. The SPs offer services to the mobile users. Four main challenges were discussed: isolation between SPs, mobility and network management, resource management, and security [21].

Kamel *et al.* [22] proposed an efficient resource allocation scheme of resource blocks in virtualized LTE networks. The problem was formulated as a mixed integer non-linear programming problem. However, due to the high complexity of solving such problems, the authors divided the problem into two sub-problems: resource allocation problem and power allocation problem. These sub-problems were solved repeatedly one after the other until an optimal solution was reached. In each iteration, the resource allocation problem was solved as a linear integer programming problem while the power allocation problem was solved using convex optimization techniques. An upper bound to the optimal solution was also given by relaxing the integer variables and transforming the problem to a regular continuous nonlinear programming problem that was solved using standard techniques [23].

Yang *et al.* [24] suggested an opportunistic spectrum sharing method that improves resource utility, revenues, and acceptance rate while decreasing the cost for virtual networks. This was done through a novel dynamic programming algorithm that solves the formulated optimization problem. Kokku *et al.* [25] presented a design and implementation of a network virtualization substrate on a WiMAX testbed. The proposed framework efficiently enabled customized flow scheduling for the different virtual networks.

Zhang *et al.* [26] described a combined time-space resource allocation scheme that took advantage of both Time Division Multiplexing and Space Division multiplexing. An empty time slot was first chosen with multiple users fitted within the slot using space multiplexing. In [27], a distributed resource allocation scheme was developed for virtualized full-duplex relaying networks.

D2D communication has also gathered significant attention as another proposed solution for satisfying the increasing data demand. Several works in the literature addressed this topic. In [16], a comprehensive survey about D2D communication, its taxonomy, and the challenges it faces was presented. The paper divides D2D communication into two main categories; Inband and Outband. Each category is further divided into two sub-categories; Underlay and Overlay Inband, and Controlled and Autonomous Outband. For underlay inband, cellular and D2D communications share the cellular spectrum while in overlay inband each type is given dedicated resources within the cellular spectrum. On the other hand, in outband D2D communication, D2D users use a different frequency band to that of cellular communication. The cellular network's advanced management features are used to control the D2D communications in controlled outband D2D. In autonomous outband D2D, D2D users regulate their requests among themselves to maintain their backlog balance at the base-station [16]. A framework for D2D-communication in 5G cellular networks was presented in [17]. A two-tier cellular network was suggested that includes a macro-tier for cellular communication and a device-tier for D2D communication. The challenges and possible solutions were also discussed.

Resource allocation in D2D communication has been a particular area of interest [28]–[31]. For example, a joint mode selection

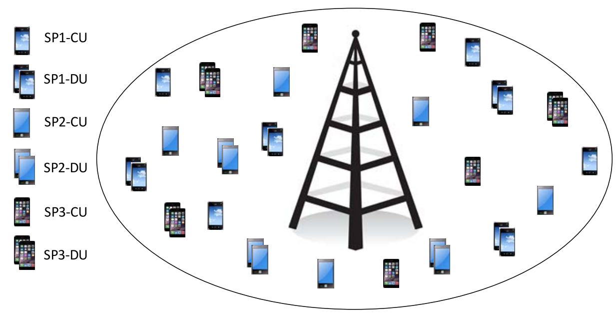

Fig. 1. System model: cellular users and device-to-device users belonging to different service providers within a single LTE cell.

and resource allocation scheme was developed in [28] that ensured the Quality-of-Service (QoS) requirements were met and the interference was suppressed. In [29], the optimal system resource allocation and mode selection for mobile content downloading was presented. Lee *et al.* [30] **proposed** a semi-distributed resource allocation scheme in which the base-station centrally allocated the radio resources for both cellular and D2D users while the modulation and coding scheme (MCS) as well as the transmission power was decided by the D2D users themselves. A resource allocation scheme that maximized the system throughput for relay-aided D2D communication under channel uncertainties was developed in [31].

In this paper, we:

- Formulate the problem of wireless resource virtualization with device-to-device communication underlaying cellular network as an integer non-linear programming problem (INLP).
- Divide the problem into two smaller linear binary integer programming problems and solve them to optimality.
- Develop two low-complexity heuristic algorithms, each to solve one of the two sub-problems.

To the best of our knowledge, no previous work addresses the topic of D2D communication in the context of resource virtualization.

III. System Model

A. General Model

We assume a single cell downlink scenario in an LTE system as is shown in Figure 1. The cell is managed by an infrastructure provider (InPr) that supports a set of service providers (SPs). The system consists of M SPs belonging to the set $\mathcal{M}_{\mathcal{SP}} = \{1, \ldots, M\}$, each serving K_m users. The K_m users are divided into C_m cellular users and D_m device-to-device (D2D) pairs; *i.e.*, $K_m = C_m + 2 \times D_m$. There are $|L|$ sub-channels in frequency, each of bandwidth B. The SPs need to be adjacent in frequency bands to enable the users to use the available sub-channels. We consider T time slots. Thus there are $T \times |L|$ resource blocks to be allocated. Each SP is assigned a minimum number of resource blocks (RBs) N^m_{RB} such that $N^m_{RB} \geq \rho^m_{min}|L|$ where ρ^m_{min} is a pre-agreed access ratio between the SPs and InPr. Isolation between the SPs is guaranteed by properly allocating the RBs to the users of the different SPs. It is assumed that the transmission powers of the base-station (BS) and the users are constant and are denoted by P_{BS} and p_u respectively. Also, the maximum distance between a D2D pair is assumed to be $d_{max} = 25m$ [14]. Furthermore, it is assumed that the BS has perfect channel state information (CSI) from all users belonging to all SPs [22]. Users are typically determined by applying an admission control algorithm to choose users with good channel conditions, a process assumed to be performed beforehand using any algorithm suggested in the literature [32]–[34].

B. Channel Model

We consider both the distance-dependent macroscopic path loss and the shadow fading path loss components. The macroscopic path loss between the eNodeB and a user at distance d in an urban environment is given by [14]:

$$L_{dB}(d) = 40\left(1 - 4 \times 10^{-3} h_b\right) \log_{10}(d/1000) - 18 \log_{10}(h_b) + 21 \log_{10}(f_c) + 80 \quad (1)$$

where h_b is the base station antenna height(in meters), f_c is the carrier frequency in MHz. The shadow fading path loss component is assumed to be a Gaussian random variable with zero mean and σ standard deviation in dB. Thus the total path loss between the eNodeB and the user is [14]:

$$PL_{dB,(BS,i)}(d) = L_{dB}(d) + \log_{10}(X_i) \quad (2)$$

where X_i is the log-normal shadow fading path loss of user i. Consequently, the linear gain between the eNodeB and a user i is [14]:

$$G_{(BS,i)} = 10^{-PL_{dB,(BS,i)}/10} \quad (3)$$

On the other hand, the channel gain between two users i and j is [14]:

$$G_{(i,j)} = K_{(i,j)} d_{(i,j)}^{-\alpha} \quad (4)$$

where $d_{(i,j)}$ is the distance between transmitter i and receiver j, α is a constant path loss exponent, and $K_{(ij)}$ is a normalization constant.

IV. Problem Formulation

It is assumed that the same assigned RB(s) allocated to a particular cellular user i is shared by one of the D2D pairs so that the total network throughput is increased. Thus, D2D pairs can not be assigned dedicated RB(s) but must share the resources with the cellular users belonging to the same SP. The optimization problem is formulated in such a way that the existing cellular network's performance is not impaired. During each scheduling round, TL RBs are available to be allocated. Furthermore, an infinitely backlogged model is assumed where users always have data to be sent. The eNodeB serves two distinct sets. Set $C = \{1, \ldots, |C_1|; 1, \ldots, |C_2|; \ldots; 1, \ldots, |C_M|\}$ represents the cellular users where $|C_1|$ is the number of cellular users belonging to SP 1, $|C_2|$ is the number of cellular users belonging to SP 2, and so forth. Set $D = \{1, \ldots, |D_1|; 1, \ldots, |D_2|; \ldots; 1, \ldots, |D_M|\}$ represents the D2D pairs with $|D_1|$ is the number of D2D pairs belonging to SP 1, $|D_2|$ is the number of D2D pairs belonging to SP 2, etc. Moreover, it is assumed that $C >> D$. C_m denotes the set of cellular users of SP m and D_m denotes the set of D2D users of SP m.

During downlink phase, a cellular user experiences interference whenever a D2D user transmits using the same allocated RB. The interference depends on two main factors, the transmit power of the D2D users and the channel gain between the cellular and D2D users. $G_{(c,d)}^{m,l}$ denotes the channel gain between cellular user c and D2D user d belonging to SP m at RB l and $G_{(BS,c)}^{m,l}$ denotes the channel gain between eNodeB and cellular user c belonging to SP m at RB l. The download signal to interference and noise ratio (SINR) of user c_m at RB l is [14]:

$$\gamma_{c_m} = \frac{\sum_{l=1}^{L_c} P_{BS,c}^{m} G_{(BS,c)}^{m,l}}{N_0 B + \sum_{d=1}^{D_m} \sum_{l=1}^{L_c} b_{(c,d)}^{m} p_d G_{(c,d)}^{m,l}} \quad (5)$$

The SINR of D2D pair d_m is [14]:

$$\gamma_{d_m} = \frac{\sum_{c=1}^{|C_m|} \sum_{l=1}^{L_c} b_{(c,d)}^{m} p_d G_{(d,d)}^{m,l}}{N_0 B + \sum_{c=1}^{|C_m|} \sum_{l=1}^{L_c} b_{(c,d)}^{m} P_{BS} G_{(BS,d)}^{m,l}} \quad (6)$$

where $b_{(c,d)}^{m}$ is a binary variable satisfying $b_{(c,d)}^{m} = 1$ if D2D pair d shares the RB(s) assigned to cellular user c, L_c is the number of RBs assigned to user c and N_0 is the noise figure and thermal noise density at the receiver, and B is the system bandwidth. We denote the rates r_c^m and r_d^m corresponding to SINR γ_{c_m} and γ_{d_m} as defined by the Shannon capacity model. Note that $G_{(BS,c)}^{m,l}$ and $G_{(BS,d)}^{m,l}$ follow equation 3 while $G_{(c,d)}^{m,l}$ and $G_{(d,d)}^{m,l}$ follow equation 4. We aim to maximize the sum rate of the cellular and D2D users. The problem can be formulated as integer non-linear program (INLP) as follows:

$$\max \sum_{m=1}^{M} \left(\sum_{c=1}^{|C_m|} n_c^m r_c^m + \sum_{d=1}^{|D_m|} \sum_{c=1}^{|C_m|} b_{(c,d)}^{m} n_c^m r_d^m \right) \quad (7a)$$

subject to

$$\sum_{l=1}^{L_c} P_{BS} G_{(BS,c)}^{m,l} \geq \gamma_{th,c}^{m} \left(N_0 B + \sum_{d=1}^{|D_m|} \sum_{l=1}^{L_c} b_{(c,d)}^{m} p_d G_{(c,d)}^{m,l} \right); \quad \forall\, c \in C_m,\ \forall\, m \in \mathcal{M}_{\mathcal{SP}} \quad (7b)$$

$$\sum_{c=1}^{|C_m|} b_{(c,d)}^{m} p_d G_{(d,d)}^{m,l} \geq \gamma_{th,d}^{m} \left(N_0 B + \sum_{c=1}^{|C_m|} \sum_{l=1}^{L_c} b_{(c,d)}^{m} P_{BS} G_{(BS,d)}^{m,l} \right); \quad \forall\, d \in D_m,\ \forall\, m \in \mathcal{M}_{\mathcal{SP}} \quad (7c)$$

$$\sum_{c=1}^{|C_m|} b_{(c,d)}^{m} \leq 1;\ \forall\, d \in D_m,\ \forall\, m \in \mathcal{M}_{\mathcal{SP}} \quad (7d)$$

$$\sum_{d=1}^{|D_m|} b_{(c,d)}^{m} \leq 1;\ \forall\, c \in C_m;\ \forall\, m \in \mathcal{M}_{\mathcal{SP}} \quad (7e)$$

$$\sum_{c=1}^{|C_m|} n_c^m = N_{RB}^m \geq \rho_{min}^m |L|; \quad \forall\, m \in \mathcal{M}_{\mathcal{SP}} \quad (7f)$$

$$n_c^m r_c^m \geq r_{c,th}^m;\ \forall c \in C_m;\ \forall\, m \in \mathcal{M}_{\mathcal{SP}} \quad (7g)$$

$$n_c^m r_d^m \geq r_{d,th}^m;\ \forall d \in D_m;\ \forall\, m \in \mathcal{M}_{\mathcal{SP}} \quad (7h)$$

The decision variables are n_c^m, an integer denoting the number of RBs allocated to cellular user c of SP m; and $b_{(c,d)}^{m}$, a binary integer denoting whether D2D user d shares the RB(s) assigned to user c of SP m. Constraints (7b) and (7c) insure that threshold SINR for both cellular and D2D users is respected. Constraint (7d) guarantees that a D2D user shares at most a particular user's RB(s) while constraint (7e) guarantees that at most one D2D user shares any user's RB(s). Constraint (7f) guarantees that each SP is allocated a minimum number of RBs as per the service level agreement **(SLA)** with the InPr such that $\rho_{min}^m \in [0, 1]$ and $\sum_{m=1}^{M} \rho_{min}^m \leq 1$. Constraints (7g) and (7h) ensure that a minimum guaranteed threshold is achieved for the cellular and D2D pairs respectively. Note that the feasibility of solving this problem is ensured by assuming an admission control process from the literature [32]–[34] is applied beforehand, which is out of the scope of this paper. Also note that this model only considers only one type of data traffic for each type of users. New constraints need to be added to the model to represent different data traffic types.

Regular non-linear or integer optimization techniques can not be applied in such a formulation since the integer decision variables lie within the log function. To be able to solve this problem, the fact that the resource allocation is for cellular users is taken advantage of since it is assumed that the cellular network's performance should not be impaired and that D2D pairs can only share already assigned RBs rather than obtaining dedicated RBs. Thus, the problem is divided into two smaller subproblems.

A. Subproblem 1: Cellular Users' Resource Allocation Problem

The optimization problem to allocate the available resources to the cellular users is formulated as follows:

$$\max \sum_{m=1}^{M} \sum_{c=1}^{|C_m|} \sum_{l=1}^{|L|} B\, x_{c,l}^{m} \log_2\left(1 + \frac{P_{BS,c}^{m} G_{(BS,c)}^{m,l}}{N_0 B}\right) \tag{8a}$$

subject to

$$\sum_{m=1}^{M} \sum_{c=1}^{|C_m|} x_{c,l}^{m} = 1;\ \forall\, l \in L \tag{8b}$$

$$N_{RB}^{m} = \sum_{l=1}^{|L|} \sum_{c=1}^{|C_m|} x_{c,l}^{m} \geq \rho_{min}^{m} |L|;\ \forall\, m \in \mathcal{M}_{\mathcal{SP}} \tag{8c}$$

$$\sum_{l=1}^{|L|} B\, x_{c,l}^{m} \log_2\left(1 + \frac{P_{BS,c}^{m} G_{(BS,c)}^{m,l}}{N_0 B}\right) \geq r_{c,th}^{m};\quad \forall\, c \in C_m;\ \forall\, m \in \mathcal{M}_{\mathcal{SP}} \tag{8d}$$

where $x_{c,l}^{m}$ is a binary variable indicating whether user c of SP m is allocated RB l, and B is the bandwidth of an RB. Constraint (8b) states that an RB can only be assigned to one cellular user. Constraint (8c) represents the SLA constraint to ensure each SP is assigned a minimum number of RBs while constraint (8d) is the minimum rate requirement for each cellular user. In this formulation, the possible interference caused by the D2D users is not considered. This will be considered in the second subproblem.

The search space for this subproblem is $(J(2^{ML} - 1))^{|C|}$ where J is the number of modulation and coding schemes (MCSs), M is the number of SPs, L is the number of RBs per SP, and $|C|$ the total number of cellular users in the cell. The problem considers J different MCSs and $(2^{ML} - 1)$ different possible resource allocation combinations for each user. For example, consider $J = 15$ MCSs, $M = 2$ SPs, $L = 6$ RBs per SP, and $|C| = 10$ cellular users, (*i.e.*, 5 cellular user per SP). The worst case search space is 7.665×10^{47}.

B. Subproblem 2: D2D Users' Resource Sharing Problem

After obtaining the optimal resource allocation solution for the cellular users, the problem of deciding which cellular user's resources will be shared by each D2D pair is solved. This problem is formulated as follows:

$$\max \sum_{m=1}^{M} \sum_{d=1}^{|D_m|} \sum_{c=1}^{|C_m|} B\, b_{(c,d)}^{m} n_c^{m} \times \log_2\left(1 + \frac{\sum_{c=1}^{|C_m|} b_{(c,d)}^{m} p_d G_{(d,d)}^{m}}{N_0 B + \sum_{c=1}^{|C_m|} b_{(c,d)}^{m} P_{BS} G_{(BS,d)}^{m}}\right) \tag{9a}$$

subject to

$$P_{BS} G_{(BS,c)}^{m} \geq \gamma_{th,c}^{m}\left(N_0 B + \sum_{d=1}^{|D_m|} b_{(c,d)}^{m} p_d G_{(c,d)}^{m}\right);\quad \forall\, c \in C_m, \forall\, m \in \mathcal{M}_{\mathcal{SP}} \tag{9b}$$

$$\sum_{c=1}^{|C_m|} b_{(c,d)}^{m} p_d G_{(d,d)}^{m} \geq \gamma_{th,d}^{m}\left(N_0 B + \sum_{c=1}^{|C_m|} b_{(c,d)}^{m} P_{BS} G_{(BS,d)}^{m}\right);\quad \forall\, d \in D_m, \forall\, m \in \mathcal{M}_{\mathcal{SP}} \tag{9c}$$

$$\sum_{c=1}^{|C_m|} b_{(c,d)}^{m} \leq 1;\ \forall\, d \in D_m,\ \forall\, m \in \mathcal{M}_{\mathcal{SP}} \tag{9d}$$

$$\sum_{d=1}^{|D_m|} b_{(c,d)}^{m} \leq 1;\ \forall\, c \in C_m,\ \forall\, m \in \mathcal{M}_{\mathcal{SP}} \tag{9e}$$

$$n_c^{m} r_d^{m} \geq r_{d,th}^{m};\ \forall\, d \in D_m;\ \forall\, m \in \mathcal{M}_{\mathcal{SP}} \tag{9f}$$

Constraint (9b) takes care of the possible interference caused to the cellular users. By ensuring that a specified SINR is maintained, the performance of the cellular users is guaranteed. On the other hand, constraint (9c) guarantees that the SINR of D2D users is also maintained. Constraint (9d) ensures that each D2D pair can only share the resources of one cellular user while constraint (9e) guarantees that at most 1 D2D pair shares the resources of each cellular user. Finally, constraint (9f) ensures that the minimum required rate for D2D pairs is satisfied.

For this subproblem, the search space is $M(J|C_m|)^{|D_m|}$ where $|C_m|$ is the number of cellular users belonging to SP m, and $|D_m|$ is the number of D2D pairs of SP m in the cell. In this case, the subproblem considers J different MCSs for $|C_m|$ cellular users for each D2D pair. For the same values suggested before ($|C_m| = 5$ and $|D_m| = 2$ D2D pairs), the search space 11250.

Solving the two subproblems to optimality is computationally expensive as the search space grows exponentially with the number of users. Thus, it is important to develop a low-complexity heuristic algorithm that can solve the problems with comparable performance.

V. HEURISTIC ALGORITHM

A. Heuristic 1: Cellular Users' Resource Allocation Problem

To solve the resource allocation problem, a heuristic algorithm that is divided into two phases is developed. In the first phase, resources are allocated to users sequentially one after the other so as to satisfy their minimum rate constraint. This is done by allocating RB(s) with the best channel gain(s) $G_{BS,c}^{m,l}$ for each user until r_c^{m}, which is calculated based on rate expression in equation (8a), satisfies the minimum rate. Then the number of RBs that have been assigned to SP m up till this point is calculated and denoted by N_c^{m}. In the second phase, the number of RBs that need to be assigned to each SP to satisfy the SLA constraint is calculated with priority given to the SP with the highest access ratio. Thus, the number of RBs already assigned to SP m and the number of RBs remaining free is determined. The algorithm is presented in Table I. The first phase is described in lines 4-14 while the second phase is described in lines 15-22 with the decision variable in line 8 being the same as in subproblem 1. The order of complexity of this algorithm is $O(L|C|)$ where L is the number of RBs available and $|C|$ is the total number of cellular users in the system ($|C| = \sum_{m=1}^{M} |C_m|$). That is due to the fact that one RB is assigned in each iteration by searching among $|C|$ possible users. Using the

TABLE I
HEURISTIC ALGORITHM FOR CELLULAR USERS' RA

$L_{tot} = \{1, 2, .., L\}$
$L_{card} = |L_{tot}|$
$M_{SP} = \{1, 2, .., M\}$
for $m \in M_{SP}$ **do**
  for $c \in C_m$ **do**
    while $r_c^m < r_{c,th}^m$ **do**
      find $g_{c,l}^m = \max_{l \in L_{tot}} \{G_{BS,c}^{m,l}\}$
      set $x_{c,l}^m = 1$
      calculate r_c^m
      update $L_{tot} = L_{tot} \setminus l$
    end while
  end for
  calculate $N_c^m = \sum_{c=1}^{|C_m|} x_{c,l}^m$
end for
for $m \in M_{SP}$ **do**
  calculate $rb^m = \rho_{min}^m L_{card} - N_c^m$
  for $r \in rb^m$ **do**
    find $g_{c,l}^m = \max_{l \in L_{tot}} \{G_{BS,c}^{m,l}\}$
    set $x_{c,l}^m = 1$
    update $L_{tot} = L_{tot} \setminus l$
  end for
end for

TABLE II
HEURISTIC ALGORITHM FOR D2D USERS' RA

$M_{SP} = \{1, 2, .., M\}$
for $m \in M_{SP}$ **do**
  sort N_c^m
  for $n_c \in N_c^m$ **do**
    while $x_{c,d}^m \neq 1 \; \forall d \in D_m$ **do**
      define $D_{temp} = \{d : x_{c,d}^m = 0\}$
      for $d \in D_{temp}$ **do**
        calculate $\gamma_{n_c,d}^m$
      end for
      find $ind_{c,d} = \max_{d \in D_{temp}} \{\gamma_{n_c,d}^m > \gamma_{c,th}\}$
      if $ind_{c,d} = \phi$ **then**
        update $N_c^m = N_c^m \setminus n_c$
      else
        set $x_{c,d}^m = 1$
        update $N_c^m = N_c^m \setminus n_c$
        update D_{temp}
      end if
    end while
  end for
end for

values suggested before, the complexity in this case is in the order of 60 operations.

B. Heuristic 2: D2D Users' Resource Sharing Problem

To solve the D2D resource allocation problem, an exhaustive-search based algorithm is employed. Since D2D pairs can only share the resources assigned to cellular users belonging to the same SP, the cellular users are sorted from the user with the highest number of RBs to the lowest. For each D2D pair, the interference it causes to the cellular user with highest number of allocated RBs is calculated. The new SINR of the cellular user is compared to the threshold SINR. The D2D pair that satisfies the SINR constraint to the cellular user and causes the least interference to it is chosen to share its RBs. If none of the D2D pairs satisfy the SINR constraint of the cellular user, the algorithm moves on to the next cellular user in the list. The algorithm is presented in Table II. The complexity of this heuristic depends on the complexity of its two parts: the sorting algorithm used first and the resource sharing decision algorithm used afterwards. For the sorting section, optimal algorithms such as the Radix sorting technique has a complexity of order $O(|C_m|)$ where $|C_m|$ is the number of elements to be sorted (which is the number of cellular users per SP) [35]. On the other hand, the resource sharing decision algorithm has a complexity of $O(|D_m| * |C_m|)$ where $|D_m|$ is the number of D2D pairs. This is because in the worst case scenario, the algorithm loops over all the cellular users for all the D2D pairs to determine which user each pair will share the resources with. Thus, the complexity would be in the order of $5+2\times5 = 15$ operations based on the values presented in the previous examples.

TABLE III
SIMULATION PARAMETERS & VALUES

Parameter	Value
Carrier frequency	2 GHz
Number of SP	3
Bandwidth per SP	10 MHz
Number of RBs per SP	50
Number of subcarriers per RB	12
Subcarrier spacing	15 KHz
RB Bandwidth	180 KHz
eNodeB Tx power	20 W
UE Tx power	250 mW = 24dBm
Slot duration	1 ms
Number of Cellular users per SP	30
Number of D2D pairs per SP	3
Cell-level user distribution	Uniform
Log-normal shadowing standard deviation	8 dB
Service Level Agreement Vector	[0.5 0.3 0.2]

VI. SIMULATION PARAMETERS AND RESULTS

A. Parameters

A system simulation using MATLAB by adopting a realistic LTE system model is performed on an Intel Core i7-4770 CPU with 16 GB RAM. When solving the D2D resource sharing problem, the SINR threshold for cellular users is assumed to be the SNR lower bounds of the MCSs used by the users [36]. Also, the rate requirement for cellular users is assumed to be 36 kbps [37]. The simulation parameters are summarized in Table III.

B. Results

Figure 2 shows the sumrate of the cellular users of each SPs. As is expected, the SP with the highest sumrate is the one with the highest access ratio based on the SLA (SP1 in this case). Moreover, as the average shadowing loss increases, the sumrate decreases because the channel is getting worse and thus users will only be able to use lower MCSs with lower spectral efficiencies.

Figure 3 shows the sumrate of the D2D pairs for each SP. It is noticed that the sumrate increases as the average shadowing loss increases. As the channel between the eNodeB and the D2D pair

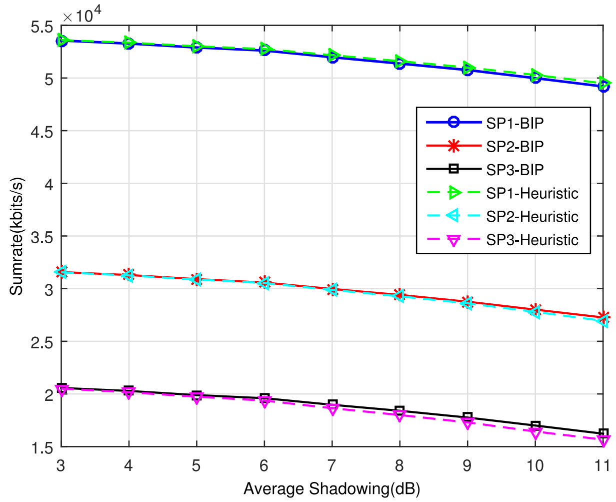

Fig. 2. Cellular users' sumrate for different SPs.

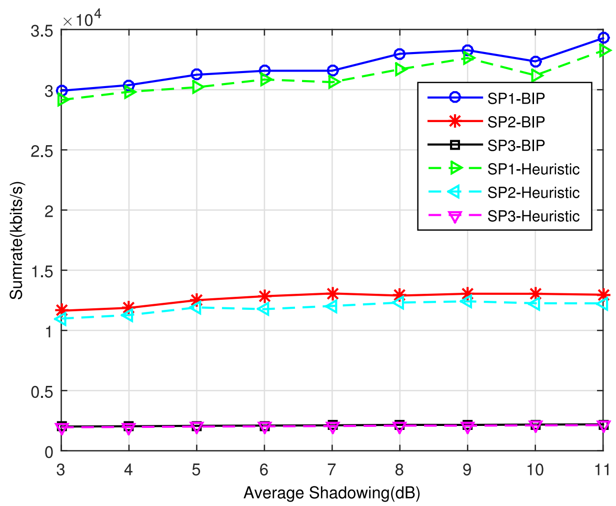

Fig. 3. D2D pairs' sumrate for different SPs.

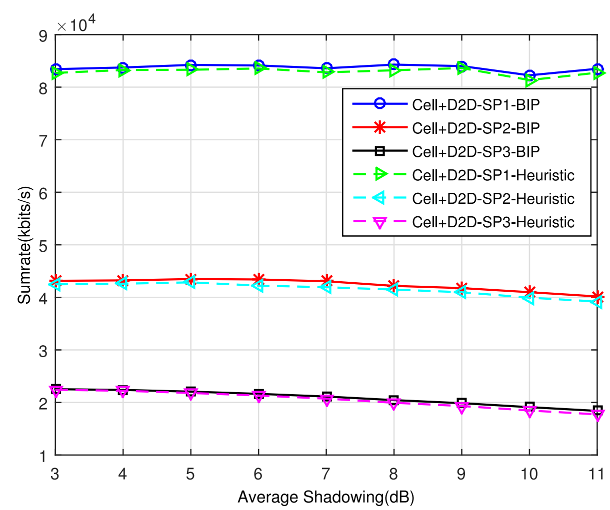

Fig. 4. System sumrate for different SPs.

becomes worse, the eNodeB causes less interference to the D2D pair. Therefore, the SINR of the D2D pairs increases allowing them to use better MCSs with higher spectral efficiencies.

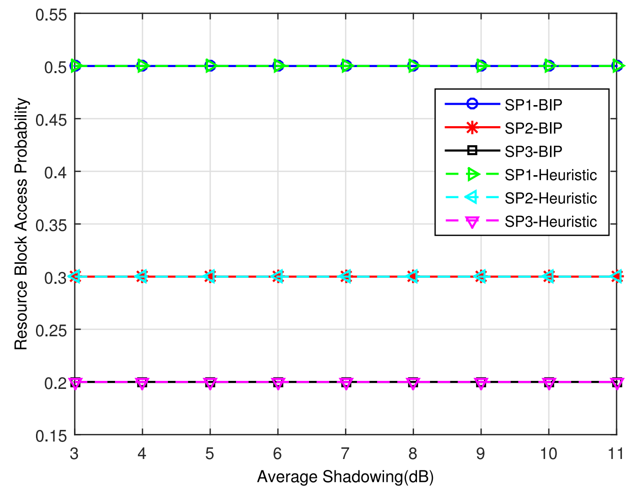

Fig. 5. Access probability of different SPs.

Figure 4 shows the sumrate of each SP. The figure shows that the D2D communication can mitigate the effect of the worsening channel conditions. Thus the overall throughput remains almost constant for different values of the average shadowing loss.

To evaluate the performance of the heuristic algorithm, it is observed that it achieves close to optimal results for both the cellular users and the D2D pairs. This is evident by the overlapping results of the BIP and the heuristic in Figures 2, 3, and 4. Furthermore, based on Figure 5, the average access probability for both the BIP and the heuristic match the ratios of the pre-agreed SLA ratios. The average runtime of both algorithms is evaluated to compare their effectiveness. The average runtime of the BIP algorithm is 19.9 ms which is much higher than that of the heuristic algorithm that achieved an average runtime of 2.6 ms. This confirms the efficiency and low complexity of the heuristic algorithm.

VII. Conclusion

In this paper, the problem of wireless resource virtualization with device-to-device (D2D) communication underlaying the LTE network was formulated. The problem is an integer non-linear programming (INLP) problem. Due to the high complexity of such problems, it was divided into two linear binary integer programming subproblems that were solved to optimality. Furthermore, two heuristic algorithms that solve each of the two subproblems were developed. Results showed that wireless resource virtualization increased the system throughput. Also, D2D communication helped mitigate the effect of worsening channel conditions. Moreover, the heuristic algorithm achieved close to optimal performance while having a much lower computational complexity.

This work can be extended in different ways. One extension will be modifying the model to include different data traffic types. This would consider a more general case as users rarely have only one type of data traffic. Another extension will be considering energy-efficient resource allocation algorithms. Reducing the transmission power at the eNodeB will result in less interference at the D2D pairs. This would allow D2D pairs to reduce their transmission power as well. Therefore, energy savings on both the eNodeB and the D2D pairs can be achieved.

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