Joint Resource Allocation in Mobile Networks with Macro Cellular and Device-to-Device Communication

Sergio Lembo, Alexis A. Dowhuszko, and Olav Tirkkonen
Department of Communications and Networking, Aalto University, P.O. Box 13000, FIN-00076 Aalto, Finland

***Abstract*—We study the joint resource allocation problem of a mobile heterogeneous network composed of macro cellular users and Device-to-Device (D2D) links. Macro cellular users are always scheduled on uplink shared resources, whereas D2D links may use uplink shared resources, orthogonal resources reserved exclusively for D2D transmissions, or a combination of both types of resources. A sum utility maximization approach is used to determine the optimal amount of orthogonal D2D resources, and the best way to allocate the remaining part of non-orthogonal uplink shared resources among macro users. An α-proportionally fair utility function is used at the macro base station to characterize the well-being of users, treating all users equally regardless of their type. Based on the centralized problem, two decentralized algorithms are derived to approximate the centralized solution with limited amounts of signaling exchange. From the observed performance results, it is possible to conclude that the proposed decentralized algorithms provide a practical way to control the average/minimum data rate in a mobile network that combines both macro cellular users and D2D links.**

I. INTRODUCTION

Device-to-Device (D2D) communication appears as one of the promising technologies to tackle the foreseen wireless traffic explosion in the following years. D2D communication underlaying cellular networks allows reusing spectrum, offloading traffic from the cellular network, reducing transmission power, and achieving higher data rates between users in close proximity [1]. In D2D communications, the scenarios can be categorized according to the kind of spectrum that is used and according to the existence (or not) of a macro cellular infrastructure to provide the required control plane functionalities. In the context of network-assisted D2D communication using licensed spectrum [1], D2D users are typically former Macro User Equipments (MUEs), offloaded from the macro cell, which should be considered as important as the other MUEs that remain being served in the macro cell. Therefore, when allocating communication resources, no distinction should be made between both types of users. To our best understanding, most of the work done in the literature has not considered this aspect in detail.

Once a D2D link is established by mode selection, there are two ways in which communication can take place. On one hand, letting the D2D links use the same communication resources used by MUEs, also known as underlaying D2D communication [1][2]. On the other hand, reserving certain amount of orthogonal dedicated resources at the Macro Base Station (MBS) for the exclusive use of D2D links. Previous work in the context of sharing non-orthogonally D2D resources with MUEs, was studied for example in [3][4][5]. Previous work in the context of reserving dedicated resources for D2D users at the MBS was done with two different approaches, reserving a fixed amount of resources [2][6], and calculating the optimal amount of resources that should be used to maximize an utility function [7][8]. To our best understanding, the simultaneous use of dedicated and shared resources for D2D users has not been considered before. Furthermore, most of the resource allocation work done in the literature considers D2D users as secondary, usually setting a constraint in the optimization problem to do not harm MUEs in terms of securing for each one a minimum data rate [5][6][7] or Quality of Service (QoS) [4][9]. This trend could be seen as a legacy from cognitive radio systems, where the common conception is that *secondary* D2D link transmissions should not generate harmful interference to *primary* MUEs. Our argument is that in the context of network assisted D2D communication, D2D users and MUEs should be treated equally when defining the optimal allocation of resources.

In this paper, we study the allocation of communication resources in a mobile network with both MUEs and D2D users. MUEs always transmit on Uplink (UL) cellular resources, which are shared with D2D transmissions. D2D users, on the other hand, transmit on UL shared cellular resources, and may optionally use communication resources reserved exclusively for D2D transmissions. The objective is to jointly optimize the allocation of resources for MUEs and D2D users. For this purpose, an optimization problem is defined, whose goal is the maximization of an α-Proportionally Fair (PF) [10] sum utility function of the data rates of both MUEs and D2D users. The sum utility function treats both type of users equally. The QoS for the users is determined by selecting the parameter α of the utility function. UL power control, and an attenuation policy for the D2D users transmitting in the shared resources, is used to avoid harmful interference from D2D transmissions at the MBS. The optimal solution of the problem is calculated by centralizing the information. This solution is based on gathering all the spectral efficiencies of the system at the MBS, which in practice is prohibitive of implementation when the number of users grows large. Then, two algorithms are derived, which provide a convenient allocation of communication resources for both MUEs and D2D links. These algorithms operate in a decentralized way, with a signaling overhead smaller than the one required in a centralized solution.

The rest of paper is organized as follows: Section II presents the system model and the main assumptions of the heterogeneous network scenario. Section III formulates the optimiza-

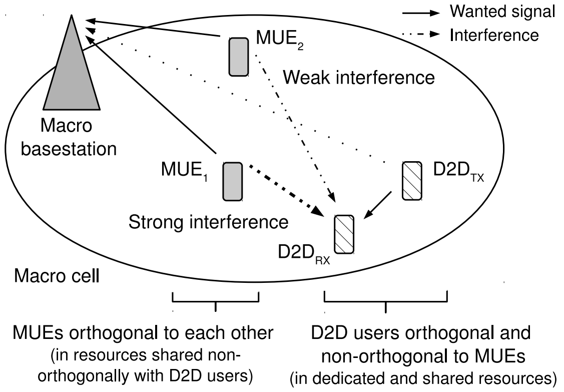

Fig. 1. Example of the mobile system under consideration with two MUEs transmitting in UL to the MBS and one D2D pair. MUE$_1$ (MUE$_2$) affects (does not affect) considerably the D2D communication.

tion problem, which is then solved analytically in Section IV. The derivation of two algorithms to approximate the solution of the centralized problem is presented in Section V. Numerical results of the different approaches are presented in Section VI. Finally, conclusions are drawn in Section VII.

II. SYSTEM MODEL

The system under consideration consists of a single macro cell with one MBS, a group of MUEs arranged in the set $\mathcal{M} = \{m_1, \cdots, m_M\}$, and a group of D2D user pairs, $\mathcal{D} = \{d_1, \cdots, d_D\}$. The cardinalities of $\mathcal{M}$ and $\mathcal{D}$, are denoted by M and D, respectively. All the MUEs transmit in UL direction to the MBS. All the D2D pairs transmit in a fixed direction, thus defining a D2D transmitter (D2D-Tx) and a D2D receiver (D2D-Rx). Hereafter, a member of the D2D pair is simply called D2D user, when it is clear from the context that the D2D user is the transmitter or receiver. It is assumed that D2D pairs have been already established by the MBS.

From the perspective of protecting MUEs, as well as for regulatory reasons, operators may prefer to allow D2D communication in UL resources [1]. In this case, MUEs in UL can interfere severely D2D-Rx. On the other hand, D2D-Tx transmission power is controlled to not produce significant interference to MUEs. Figure 1 depicts an example of two MUEs and one D2D pair. In the figure, MUE$_1$ is close to a D2D-Rx, producing a high interference, whereas MUE$_2$ is far away, producing less interference. D2D users transmit non-orthogonally to MUEs, but in the case that the interference of MUEs is significant, D2D users may need to use their own exclusive orthogonal resources (free of MUEs interference) to make communication possible.

In the following analysis there is no particular emphasis on the nature of the radio resources (i.e., frequency, time), and these are simply called *resources*. MUEs are always scheduled by the MBS in orthogonal resources. On the other hand, D2D users are capable of transmitting in two types of resources. First, D2D users can transmit in shared non-orthogonal resources with respect to the MUEs, i.e. underlying MUEs transmissions. Throughout the paper these resources are termed *non-orthogonal resources* (see Fig. 2). We emphasize that these resources are orthogonal for MUEs, and at the same time, are shared non-orthogonally with D2D users. Second, D2D users can also transmit in orthogonal resources with respect to the MUEs. These resources are exclusively dedicated, and common, to all the D2D users, and are termed *orthogonal resources* (see Fig. 2).

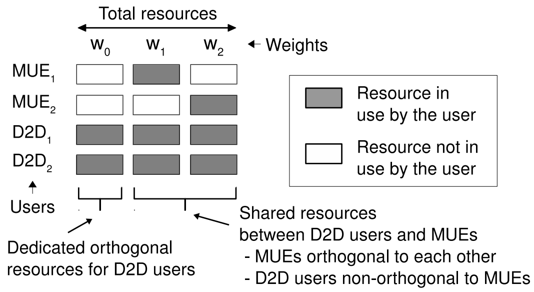

Fig. 2. Example of use of resources by two MUEs and two D2D pairs.

With the proposed arrangement, D2D orthogonal resources are reserved exclusively for D2D users by muting all the MUE transmissions; thus letting D2D users operate free of UL interference from MUEs. The amount of resources given to the users is represented by a scheduling weight w_j, with j being an index associated to an orthogonal resource, as depicted in Fig. 2. An optimal solution will balance the amount of orthogonal resources given to D2D users, and the amount of shared resources given to MUEs and D2D users.

In the model under consideration in this paper it is assumed that there is uplink power control in all the users of the system. As a protection measure for the cellular users, we determine an attenuation policy for the D2D users in the shared non-orthogonal resources. Thus when D2D users transmit in resources where there is an UL transmission in the same cell, the transmission power is selected according to the cellular power control principle, with a security margin that makes the interference from this transmission negligible at the MBS. In orthogonal resources, the D2D transmission powers are again selected according to the cellular power control principle, but now in such a manner that the total average radiated power from a cell is the same in orthogonal and non-orthogonal resources. Under this assumption, ideally, there is no need to coordinate D2D transmissions to avoid interfering MUEs reception at the neighboring cells. We are interested in resource optimization between cellular and D2D users. There may be strong interference between D2D-Tx with a D2D-Rx from another D2D pair. Here, we do not concentrate on interference coordination between D2D pairs. Among themselves, all the D2D users transmit simultaneously in the shared, and in the dedicated orthogonal resources.

III. PROBLEM STATEMENT

To formulate an optimization problem allowing analytical treatment, we need an utility function that characterizes the whole system. We attempt a joint optimization of the MUEs and D2D users with the aid of a common sum utility function. The assumption is that the users are, in general, of the same type, and can use either cellular or D2D connections. The happiness of the users can be characterized by a function of the data rate, irrespectively of the type of communication in which the user is participating at the moment. We do not consider the option of cellular mode transmission [2] for the D2D pairs—a D2D pair always communicates directly.

To simplify the analysis we assume that all resources are equal for the users. Thus neither time nor frequency selective fading is considered. With a fixed power control policy, like e.g. the open-loop power control of LTE [11], the transmit power of a MUE is fixed, and the data rate of the users becomes directly proportional to the amount of resources given to the user. The data rate of a MUE $m \in \mathcal{M}$ is given by

$$x_m = r_m w_m, \tag{1}$$

where r_m is the, non-zero, spectral efficiency of MUE m, and w_m is the scheduling weight of resources allocated to the MUE. Recall that these resources are shared non-orthogonally with D2D communication. Similarly, the data rate of a D2D user $d \in \mathcal{D}$ is

$$x_d = \sum_{m \in \mathcal{M}} r_{d|m} w_m + r_{d|0} w_0, \tag{2}$$

where $r_{d|m}$ is the spectral efficiency of D2D user d when transmitting simultaneously with MUE m, and $r_{d|0}$ is the, non-zero, spectral efficiency of the D2D user d when no MUE is transmitting. The scheduling weight of resources allocated to D2D transmissions only, orthogonal to MUEs, is denoted w_0.

Formally, we may collect all the spectral efficiencies to a matrix $\mathbf{R}$, the data rates of the D2D users and the MUEs to a vector $\mathbf{x}$, and the scheduling weights to a vector $\mathbf{w}$. Then (1) and (2) are expressed in vectorial form as

$$\mathbf{x} = \mathbf{R}\mathbf{w}. \tag{3}$$

We assume that there is a utility function characterizing the user well-being. For concreteness we use the α-PF utility function [10],

$$u(x) = \begin{cases} \log(x) & \text{for } \alpha = 1 \\ (1-\alpha)^{-1} x^{1-\alpha} & \text{for } \alpha \neq 1 \end{cases}. \tag{4}$$

The sum utility function, of the data rates of all the users, is

$$U = \sum_{m \in \mathcal{M}} u(x_m) + \sum_{d \in \mathcal{D}} u(x_d) = \sum_{i=1}^{M+D} u\left(\mathbf{r}^i \mathbf{w}\right), \tag{5}$$

where $\mathbf{r}^i$ denotes the ith row of $\mathbf{R}$.

The optimization problem consists in maximizing the concave function U over the set of scheduling weights $\mathbf{w}$, i.e.,

$$\begin{aligned} &\mathbf{w}^* = \arg\max_{\mathbf{w}} U \\ &\text{s.t.} \quad w_j \geq 0,\ j = 0, \ldots, M; \quad \sum_{j=0}^{M} w_j = 1. \end{aligned} \tag{6}$$

For convenience, it is good to look at the matrix $\mathbf{R}$ in more detail. It is of size $(M+D)$ by $(M+1)$, and it is constructed by a concatenation of sub-matrices and vectors as follows:

$$\mathbf{R} = \left[\begin{array}{c|c} \mathbf{0}_M & \mathbf{R}_{\mathcal{M}} \\ \hline \mathbf{r}_{\mathcal{D}|0} & \mathbf{R}_{\mathcal{D}|\mathcal{M}} \end{array} \right], \tag{7}$$

where

$$\mathbf{R}_{\mathcal{M}} = \operatorname{diag}\left(r_m : m \in \mathcal{M}\right) \tag{8}$$

is a diagonal matrix with the spectral efficiencies of MUEs,

$$\mathbf{R}_{\mathcal{D}|\mathcal{M}} = \left[\mathbf{r}_{d_1|\mathcal{M}}, \mathbf{r}_{d_2|\mathcal{M}}, \cdots, \mathbf{r}_{d_D|\mathcal{M}}\right]^T \tag{9}$$

contains the spectral efficiencies of the D2D users in resources interfered by other D2D users and one MUE. Specifically, the rates of one D2D user are in the vector

$$\mathbf{r}_{d_i|\mathcal{M}} = \left[r_{d_i|m_1}, r_{d_i|m_2}, \cdots, r_{d_i|m_M}\right]^T, \tag{10}$$

The vector

$$\mathbf{r}_{\mathcal{D}|0} = \left[r_{d_1|0}, r_{d_2|0}, \cdots, r_{d_D|0}\right]^T, \tag{11}$$

contains the spectral efficiencies of D2D users when no MUE is transmitting, and interference is from the other D2D users only. Vector $\mathbf{0}_M$ is a column vector of M zeros.

IV. CENTRALIZED ANALYTIC SOLUTION

The sum utility can be maximized by a gradient search algorithm, which requires a centralized knowledge of matrix $\mathbf{R}$ at the MBS. The construction of $\mathbf{R}$ has the cost of each D2D user d reporting the corresponding row of $\mathbf{R}$, which is not practical when the number of MUEs and D2D users grows large. With the aim of implementing a decentralized solution, we proceed to derive an analytic solution for the calculation of $\mathbf{w}$, which will be used as a building block in the algorithms to be presented in the next section.

The Lagrangian of the problem (6) is,

$$L = \sum_{i=1}^{M+D} u\left(\mathbf{r}^i \mathbf{w}\right) + \lambda \left(1 - \sum_{j=0}^{M} w_j\right) + \sum_{j=0}^{M} \mu_j w_j, \tag{12}$$

where λ and μ_j, for $j = 0, \ldots, M$, are the Lagrange multipliers for the equality and non-equality constraints.

The KKT conditions of the problem (12) are, in addition to the constraints in (6), the following:

$$\mu_j w_j = 0, \quad \frac{\partial L}{\partial w_j} = 0, \quad \mu_j \geq 0; \quad j = 0, \ldots, M. \tag{13}$$

From the derivative in (13) we have that

$$\sum_{i=1}^{M+D} u'\left(\mathbf{r}^i \mathbf{w}\right) r_{ij} - \lambda + \mu_j = 0, \qquad j = 0, \ldots, M. \tag{14}$$

Arranging terms and writing in matrix notation we have

$$\mathbf{R}^T\, \mathbf{f}^{-1}\left(\mathbf{R}\mathbf{w}\right) = \lambda \mathbf{1} - \boldsymbol{\mu}, \tag{15}$$

where $\mathbf{f}$ is a vector valued function,

$$\mathbf{f}(\mathbf{v}) = [v_1^{-1/\alpha}, v_2^{-1/\alpha}, \cdots, v_n^{-1/\alpha}], \tag{16}$$

with $\mathbf{v} = [v_1, v_2, \cdots, v_n]$. The function is equivalent to the scalar function $u'^{-1}(x) = x^{-1/\alpha}$, operating element-wise on each element of the vector $\mathbf{v}$. Vectors $\mathbf{1}$ and $\boldsymbol{\mu}$ are column vectors of length $M+1$, containing ones and the multipliers μ_j, respectively.

An analytical solution of the weights can be obtained from (15) when $\mathbf{R}$ is a square matrix. In this case

$$\mathbf{w} = \mathbf{R}^{-1}\, \mathbf{f}\left(\mathbf{R}^{T^{-1}} \left(\lambda \mathbf{1} - \boldsymbol{\mu}\right)\right). \tag{17}$$

Note that this happens when $D = 0$ or $D = 1$. These solutions are of interest for the decentralized algorithms to be presented.

A. Solution for M MUEs and one D2D user

When $D = 1$, $\mathbf{R}$ is a square matrix of dimension $(M+1) \times (M+1)$; the weights for this system can be calculated from (17). It can be shown that in a system with M MUEs and one D2D user, the weights w_m, for $m = 1, \ldots, M$ cannot be zero for $\alpha > 0$, by solving each w_m from (17). Thus, from complementary slackness (13), it follows that in a system with M MUEs and one D2D user, the Lagrange multipliers μ_m, for $m = 1, \ldots, M$, are zero for $\alpha > 0$.

Under the assumption that D2D orthogonalization is needed, i.e. $w_0 > 0$, from complementary slackness the corresponding multiplier is $\mu_0 = 0$. Thus, when there is one D2D pair and an orthogonal D2D resource, $\boldsymbol{\mu} = \mathbf{0}$. From (17), removing λ out from the element-wise exponent, and using (6), we have

$$\lambda = \left(\mathbf{1}^T \left[\mathbf{R}^{-1}\, \mathbf{f}\left(\mathbf{R}^{T^{-1}}\mathbf{1}\right)\right]\right)^{\alpha}. \qquad (18)$$

If for a particular solution the true value of w_0 is 0, the value of w_0 resulting from using this λ in (17) is negative, due that actually $\mu_0 > 0$. In this case we should solve for μ_0 to be able to calculate $\mathbf{w}$. This is not an easy task, due to the element-wise operation of $\mathbf{f}$. Nevertheless, by looking at the sign of w_0 we can answer whether D2D orthogonalization is needed or not, and if it is needed, we can calculate the value of w_0.

B. Solution for M MUEs and no D2D users

When there are no D2D users in the system, or when the D2D users are ignored in the allocation of resources, $\mathbf{R}$ is given by $\mathbf{R}_{\mathcal{M}}$ in (8). This gives a resource allocation optimized only for MUEs, ignoring D2D users, and serves as a lower bound in system performance. The situation with $D = 0$ can be solved as above, with $\boldsymbol{\mu} = \mathbf{0}$ and λ given by (18).

V. APPROXIMATE DECENTRALIZED SOLUTIONS

The analytical solution for one D2D user is now extended for any number of D2D users in the following two decentralized algorithms. The algorithms approximate the resource allocation solution in a decentralized way, requiring less signaling information than in a centralized system.

A. Algorithm with D2D Orthogonal Resource Request (D-ORR)

This method is based on calculating the individual requirements of orthogonal resources for each D2D user, and then aggregating these at the MBS. With the assumption that the MUE spectral efficiencies $\mathbf{R}_{\mathcal{M}}$ are broadcasted toward the D2D users, each D2D user is capable to construct a matrix for the case $D = 1$, considering itself to be the only D2D pair present in the system. Each D2D user then calculates, in a decentralized way, a solution for a system with one D2D user using (17) with the aid of (18) and $\boldsymbol{\mu} = \mathbf{0}$. Then, the value of the orthogonalization weight w_0 is reported to the MBS. The MBS aggregates the reported weights, $w_0^{(d)}$, by a suitable function into a global orthogonalization weight $\hat{w}_0$. E.g. selecting the maximum weight, $\hat{w}_0 = \max({w_0}^{(d)})$. Then the sub-optimal allocation of resources $\hat{\mathbf{w}}$, with elements $\hat{w}_j$, for $j = 0, \ldots, M$, is calculated. The proposed algorithm is presented as Algorithm 1. In this algorithm, the signaling overhead is the introduced by broadcasting M real numbers for the spectral efficiencies of MUEs, and from one real number reported by each D2D to the MBS to request orthogonal resources.

Algorithm 1 D2D Orthogonal Resource Request (D-ORR)

```
    Broadcast phase (Action at the MBS):
MBS broadcasts matrix of spectral efficiencies $\mathbf{R}_{\mathcal{M}}$ to D2D users
    Decentralized calculation (Action at D2D users):
for d = 1 to D do
    D2D $d$ constructs matrix $\mathbf{R}$ for the case $D = 1$
    Calculate orthogonalization weight $w_0^{(d)}$ using $\boldsymbol{\mu} = \mathbf{0}$, (18) and (17)
    if $w_0^{(d)} < 0$ then
        $w_0^{(d)} \leftarrow 0$ (no need of orthogonal resources)
    end if
    D2D $d$ communicates $w_0^{(d)}$ to the MBS
end for
    Resources Allocation (Action at the MBS):
Aggregation of reported weights by D2D users: $\hat{w}_0 \leftarrow \max({w_0}^{(d)})$
Calculate macro weights, $\tilde{w}_j$, for $j = 1, \ldots, M$, ignoring D2D users,
    using $D = 0$ in (17)
$\hat{w}_j \leftarrow (1 - \hat{w}_0)\tilde{w}_j$, $j = 1, \ldots, M$ (weights for shared resources)
Output: $\hat{\mathbf{w}}$ (with elements $\hat{w}_j$, for $j = 0, \ldots, M$)
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B. Algorithm with MUE Classification (M-C)

A simpler algorithm is motivated by the D2D-Cellular user pairing concept [3][4][5]. Each D2D user determines which MUEs are candidates for pairing, by classifying them as *affecting* or *non-affecting* to the D2D transmission. For this, a calculation in a 2 by 2 sub-matrix of $\mathbf{R}$ is done, involving MUE m and D2D user d as follows:

$$\mathbf{R}_{m,d} = \begin{bmatrix} 0 & r_m \\ r_{d|0} & r_{d|m} \end{bmatrix}. \qquad (19)$$

The D2D users report the perceived classification of the MUEs to the MBS, then this information is used along with statistical data to determine a sub-optimal resource allocation.

1) Determination of Affecting/Non-affecting MUEs: Matrix $\mathbf{R}_{m,d}$ is square of dimension 2×2, the weights for this system are calculated from (17). Using $\boldsymbol{\mu} = 0$ in (17) allows to determine whether a MUE is affecting or non-affecting in a 2×2 sub-problem. With $\boldsymbol{\mu} = \mathbf{0}$, we would have a λ of the form (18). Using this in (17), would give us w_0 and w_m. The effect of the MUE m under evaluation towards the D2D user d is determined by looking at the value of the sign in the weight w_0. If $w_0 > 0$, MUE m is affecting to D2D d, otherwise MUE m is non-affecting to D2D d.

The results on the effect of each MUE against each D2D user are signaled to the MBS and summarized in a $D \times M$ matrix $\mathbf{A}$, in which $a_{d,m} = 1$ if the MUE is affecting, and $a_{d,m} = 0$ otherwise. This information is then aggregated per MUE, with the criterion that if there exists at least one D2D user being affected by a MUE, then the MUE is declared as affecting MUE in the global solution. From this classification we determine the number of affecting MUEs, N_{ma}, and the number of non-affecting MUEs, N_{mn}.

2) Calculation of resources: Once the MUEs are classified, we determine the amount of orthogonal D2D resources that are needed. For this purpose we assume that all the MUEs get the same amount of resources W_m, which is a correct assumption for the case $\alpha = 1$, proportionally-fair. An amount of resources

$$W_{\mathrm{d}} = 1 - MW_m \tag{20}$$

is allocated to D2D users in dedicated orthogonal resources. We assume that the average spectral efficiency of D2D users in the resources of an affecting macro user is R_{dma}, and in resources of a non-affecting macro user is R_{dmn}. So, the expected spectral efficiency of D2D users is then

$$R_{\mathrm{a}} = N_{\mathrm{ma}} R_{\mathrm{dma}} + N_{\mathrm{mn}} R_{\mathrm{dmn}}, \tag{21}$$

where,

$$M = N_{\mathrm{ma}} + N_{\mathrm{mn}}. \tag{22}$$

The total expected spectral efficiency of D2D users is

$$X_{\mathrm{d}} = R_{\mathrm{a}} W_{\mathrm{m}} + R_{\mathrm{d}} W_{\mathrm{d}}, \tag{23}$$

where R_{d} is the average spectral efficiency of all D2D users in dedicated orthogonal resources. Finally, the total expected spectral efficiency of MUEs is

$$X_{\mathrm{m}} = R_{\mathrm{m}} W_{\mathrm{m}}, \tag{24}$$

where R_{m} is the average spectral efficiency of all MUEs.

The α-PF sum utility function of the simplified system becomes

$$\tilde{U} = \frac{D X_{\mathrm{d}}^{1-\alpha}}{1-\alpha} + \frac{M X_{\mathrm{m}}^{1-\alpha}}{1-\alpha}. \tag{25}$$

The objective is to maximize the sum utility. The Lagrangian of the function to optimize is

$$\tilde{L} = \tilde{U} - \tilde{\lambda}(MW_{\mathrm{m}} + W_{\mathrm{d}} - 1), \tag{26}$$

where $\tilde{\lambda}$ is the Lagrange multiplier for this problem. Finding the extrema with respect to the weights, $\partial\tilde{L}/\partial W_{\mathrm{m}} = 0$, and, $\partial\tilde{L}/\partial W_{\mathrm{d}} = 0$, and solving for W_m we obtain

$$W_m = \frac{R_{\mathrm{d}}}{R_{\mathrm{m}}\left(\frac{MR_{\mathrm{m}}}{DMR_{\mathrm{d}} - DR_{\mathrm{a}}}\right)^{-1/\alpha} + MR_{\mathrm{d}} - R_{\mathrm{a}}}, \tag{27}$$

where R_{a} is defined in (21) and M in (22). If $W_{\mathrm{m}} > 1/M$, set $W_{\mathrm{m}} = 1/M$. Finally, the amount of orthogonal resources for the D2D users, W_{d}, is calculated from (20).

The calculation of W_m requires the average spectral efficiencies, R_{dma}, R_{dmn}, R_{d}, R_{m}, which should be estimated from historic statistical information in the system. The algorithm in summarized in Algorithm 2. The final vector of weights for the whole system is $\hat{\mathbf{w}}$, with elements $\hat{w}_j$, for $j = 0, \ldots, M$. The signaling overhead is the introduced by broadcasting M real numbers for the spectral efficiencies of MUEs, and from the M affecting/non-affecting binary values reported by each D2D to the MBS.

VI. SIMULATION RESULTS

The proposed algorithms are evaluated in a system simulator. Performance is compared against a centralized solution, where it is assumed that all the D2D users report their spectral efficiencies to the MBS. This is regarded as the upper bound in system performance to which we want to approximate. Performance is also compared against a solution that considers only MUEs in the optimization, which is regarded as the lower bound in system performance.

Algorithm 2 MUE Classification (M-C)

```
Broadcast phase (Action at the MBS):
MBS broadcasts matrix of spectral efficiencies $\mathbf{R}_{\mathcal{M}}$ to D2D users
Decentralized calculation (Action at D2D users):
for d = 1 to D do
    for m = 1 to M do
        Construct $2 \times 2$ matrix $\mathbf{R}_{m,d}$
        Calculate orthogonalization weight $w_0$ using $\boldsymbol{\mu} = \mathbf{0}$, (18), (17)
        if $w_0 > 0$ then
            $a_m^{(d)} \leftarrow 1$ (MUE $m$ is affecting to D2D $d$)
        else
            $a_m^{(d)} \leftarrow 0$ (MUE $m$ is non-affecting to D2D $d$)
        end if
    end for
    Inform affecting classification vector $\mathbf{a}^{(d)}$ to the MBS
end for
Resources Allocation (Action at the MBS):
$\mathbf{A} \leftarrow [\mathbf{a}^{(1)}, \mathbf{a}^{(2)}, \ldots, \mathbf{a}^{(D)}]^T$ (gather affecting classification in $\mathbf{A}$)
Aggregation of reported MUEs classification: from $\mathbf{A}$, a MUE is declared
    as affecting in the global solution if it affects at least one D2D link
$N_{\mathrm{ma}} \leftarrow$ number of affecting MUEs
$N_{\mathrm{mn}} \leftarrow$ number of non-affecting MUEs
Calculate $W_m$ using (27), if $W_{\mathrm{m}} > 1/M$ set $W_{\mathrm{m}} = 1/M$, and $W_{\mathrm{d}}$
    using (20)
$\hat{w}_0 \leftarrow W_{\mathrm{d}}$ (orthogonal weight for D2D users)
Calculate macro weights, $\tilde{w}_j$, for $j = 1, \ldots, M$, ignoring D2D users,
    using $D = 0$ in (17)
$\hat{w}_j \leftarrow (1 - W_{\mathrm{d}})\tilde{w}_j$, $j = 1, \ldots, M$ (weights for shared resources)
Output: $\hat{\mathbf{w}}$ (with elements $\hat{w}_j$, $j = 0, \ldots, M$)
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TABLE I
PARAMETERS OF SCENARIO

Parameter	Setting
Macro cell radius (sectors)	500 meters (120 degrees)
Number of MUEs (D2D pairs)	$M = 6$ ($D = 4$)
Distribution of MUE and D2D users	Uniform in cell sector
D2D-Tx to D2D-Rx distance	20 meters
Other interferences	None
Antenna gain MBS (D2D-Rx)	14 dBi (0 dBi)
Noise figure MBS (D2D-Rx)	5 dB (9 dB)
Shadow fading (Fast fading)	None (Block Rayleigh fading)
Thermal noise level	-174 dBm / Hz
Path loss model	$L = 128.1 + 37.6 \log_{10} d$ d: distance in km.
P_0 (Target UL Rx Power)	-170.65 dBm / Hz
SINR to Rate mapping	Shannon rate formula

A. Simulation scenario

The system simulator is a custom made simulator for a Macro-D2D scenario in UL. The simulation scenario consists of a 120 degrees sector of a circular cell, with one MBS in the center of the cell. In each simulation instance, users are placed in random locations as follows. MUEs and D2D-Rx are uniformly distributed in the sector, but no closer than 10 meters from the MBS. D2D-Tx are located at a fixed distance of the D2D-Rx, with an uniformly distributed angular position. Additional parameters of the simulator are listed in Table I.

MUEs transmit in UL direction. UL power control sets MUE Tx power to target the received power P_0 [11]. The setting of the D2D-Tx transmission power is according to the impact it makes in the MBS as follows. In non-orthogonal resources D2D-Tx power is set to interfere the MBS with a power $(P_0 - \Delta\mathrm{dB})/\mathrm{D}$, with $\Delta\mathrm{dB} = 20\mathrm{dB}$. In orthogonal resources for the D2D users, D2D-Tx power is set to reach the MBS with a power P_0/D. The normalization by D is done to control the interference radiated towards the adjacent cells and make it equivalent to the power radiated by one MUE in the target cell. Thus, the inter-cell interference in D2D orthogonal resources is in the same order as the one generated in MUE orthogonal resources. Finally, it is assumed that all the users in the system have an infinite buffer of data to transmit.

B. Results

Simulations are executed along 1000 network instances for each value of α. In each instance, a matrix of spectral efficiencies $\mathbf{R}$ is generated for the given number M and D, see (8). From this matrix we calculate a centralized solution of the scheduling weights using a gradient search algorithm, and a centralized solution considering only MUEs, ignoring the presence of D2D users. In addition, we obtain approximate solutions using the two proposed algorithms.

Results are evaluated in terms of mean and 5% percentile of the users' data rate. Results represent the different trade-offs that can be achieved between sum rate maximization and fair share of data rates among the users. Figure 3 shows the performance achieved for a case with 6 MUEs and 4 D2D users, considering all the users in the system. First we should look at the optimal solution (solid line with stars), obtained by collecting all the spectral efficiencies of the users at the MBS, and solving the optimization problem using gradient search. Note that this is the upper bound solution to which we want to approximate with the decentralized algorithms. Then, we observe the solution obtained by considering only the MUEs in the optimization (solid line). Such solution represents the performance when D2D users are regarded as secondary users, ignoring them in the optimization process. Next, we observe that the decentralized algorithm M-C performs close to the centralized solution for $\alpha < 1$ (sum-rate maximization), and starts to deviate as α grows larger than 1. Let us recall that in the derivation of this algorithm, we made an assumption only valid for $\alpha = 1$. The decentralized algorithm D-ORR does not perform as accurate as the centralized solution, but provides a better solution than M-C algorithm for larger α (fairness). Both decentralized algorithms provide a performance that is significantly better than the one obtained in the solution considering only MUEs.

VII. CONCLUSION

We studied the resource allocation problem in a mobile network consisting of MUEs and D2D users. MUEs always transmit in uplink shared resources, whereas D2D links transmit non-orthogonally to MUEs and may optionally utilize orthogonal resources reserved exclusively for D2D transmissions. The objective was the joint optimization of communication resources for both MUE and D2D users. For this purpose, an optimization problem was defined, whose goal was the maximization of an α-proportionally fair sum utility function of the data rates of both MUEs and D2D links. Two decentralized algorithms, known as M-C and D-ORR, were derived. Both algorithms approximated the solution of the centralized problem requiring less signaling overhead. Algorithm M-C works very well for sum-rate maximization and proportionally fair utility maximization. Algorithm D-ORR shows a better performance for more fairness than proportional fairness. From the observed performance results, it is possible to conclude that the proposed algorithms provide a practical way to control the average/minimum data rate in a mobile network that combines macro cellular users and D2D links.

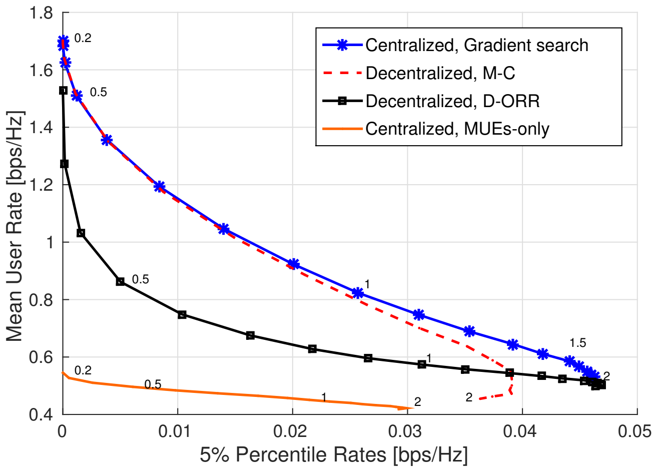

Fig. 3. Performance experienced by the users in the mobile network.. $M = 6$, $D = 4$, $0.2 \leq \alpha \leq 2$. Numbers denote α. Results represent the different trade-offs that can be achieved between sum rate maximization and fair share of data rates among the users.

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